1966

Syntheses and eliminations of cyclopentyl derivatives

David John Rausch
Iowa State University

66–6996

RAUSCH, David John, 1940–

SYNTHESES AND ELIMINATIONS OF
CYCLOPENTYL DERIVATIVES.

Iowa State University of Science and Technology
Ph.D., 1966
Chemistry, organic

SYNTHESES AND ELIMINATIONS OF CYCLOPENTYL DERIVATIVES

by

David John Rausch

A Dissertation Submitted to the

Graduate Faculty in Partial Fulfillment of

The Requirements for the Degree of

DOCTOR OF PHILOSOPHY

Major Subject: Organic Chemistry

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

Head of Major Department

Signature was redacted for privacy.

Dean of Graduate College

Iowa State University
Of Science and Technology
Ames, Iowa

1966

TABLE OF CONTENTS

VITA

The author was born in Aurora, Illinois, on October 24, 1940, to Mr. and Mrs. John Rausch. He attended high school at Marmion Military Academy in Aurora and was graduated in June, 1958. In September of the same year he enrolled at St. Procopius College at Lisle, Illinois. The author was awarded an undergraduate National Science Foundation research grant during the summer of 1961 and academic year 1961-62. In June, 1962, he received his Bachelor of Science degree from St. Procopius College.

In July of 1962, the author began his graduate studies at Iowa State University as a teaching assistant in organic chemistry under Dr. C. H. DePuy. In August of that year he married Gertrude Miller. During his residence in graduate school, his family increased with the addition of a girl in November, 1963 and a boy in July, 1965. After teaching for two years, the author received a Shell Companies Foundation fellowship in September, 1964. The author was graduated with a Ph.D. degree from Iowa State University of Science and Technology in February, 1966.

The author has accepted a post-doctoral position to further his studies under Professor H. L. Goering at the University of Wisconsin at Madison.

INTRODUCTION

Many investigations have been carried out in the last 10 to 15 years seeking to elucidate a detailed three-dimensional structure of substituted cyclohexyl compounds. At the same time, relatively little consideration has been given to the correlation of conformation with the physical and chemical properties in cyclopentane derivatives. Two general methods have been employed in conformational analysis to determine the preferred spatial arrangements of organic molecules. Contained in the first category are physical methods such as electron and X-ray diffraction measurements, calorimetric determination of energy contents of compounds, and measurements of dipole moments and spectra (Raman, infrared, microwave, ultraviolet, nuclear magnetic resonance, and optical rotatory dispersion). In the second category are the chemical methods. These concern experiments from which predictions on the conformation of a molecule can be made, based on certain reactions of model compounds. Thus far only a few of the many available reactions have been investigated for their usefulness in conformational analysis.

The primary purpose of this work was to synthesize substituted cyclopentyl derivatives and determine a relationship between the conformations of the five-membered rings using as criteria the chemical reactivity and product ratios of the derivatives. Equilibration of the substituted alcohols, epoxidation of the olefins with subsequent reduction to the alcohols, hydroboration of the olefins, vapor phase pyrolysis of the acetates, and base catalyzed elimination and solvolysis of the derived bromides and p-toluenesulfonates were reactions studied to deter-

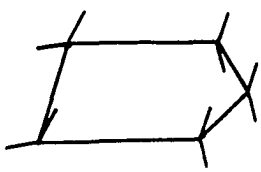
mine the significance of conformational effects on reaction mechanisms. The effect of the base/solvent system, effect of the leaving group, and effect of changing the dihedral angle between the beta-proton and the leaving group on the transition state in the base catalyzed elimination reactions (E2) in these systems were also studied.

HISTORICAL

Conformation of Cyclopentanes

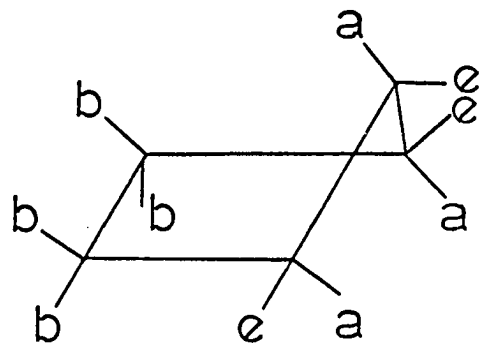
Originally, the cyclopentane ring was believed to be a planar molecule, since in this form the internal angle of the regular pentagon (108^{o}) is very close to the tetrahedral carbon bond angle ($109^{o}28'$) (1). Planar cyclopentane would, however, have five eclipsed methylene groups, leading to a bond opposition strain (2) (Pitzer strain) of 14.0 kcal./mole (3). The origin of Pitzer strain lies in a repulsion of neighboring, nonbonded atoms.

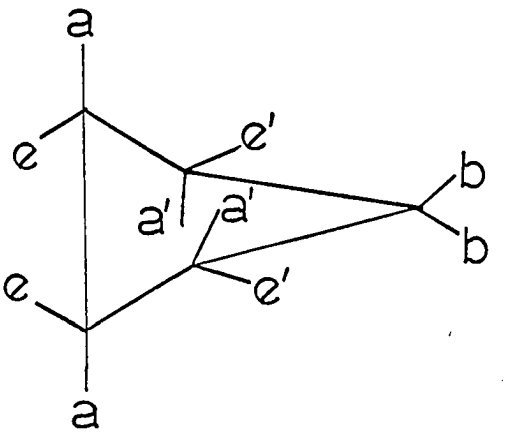
If one compares the heat of combustion per CH_2 group of cyclopentane (158.7 kcal./mole) with that of cyclohexane (157.4 kcal./mole) or the normal value per CH_2-group in open-chain aliphatic compounds (157.5 kcal./mole), a definite increase of the heat of combustion of cyclopentane is observed. From the heats of combustion data a higher energy content is estimated for cyclopentane in comparison to open chain compounds which amounts to 6-7 kcal./mole (4). This higher energy content cannot be related to Baeyer strain (angle strain), but seems to result from the nearly completely eclipsed hydrogen atoms of the adjacent methylene groups. In order to minimize this eclipsing strain, cyclopentane assumes a puckered form, the increase in angle strain thus arising (4.3 kcal./

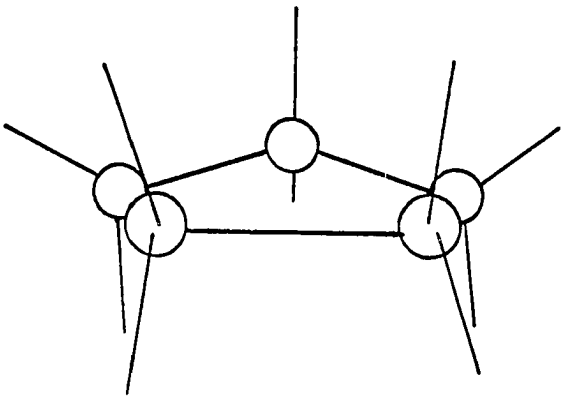


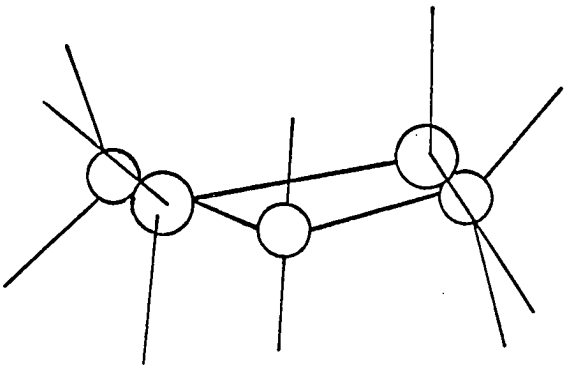
(1)

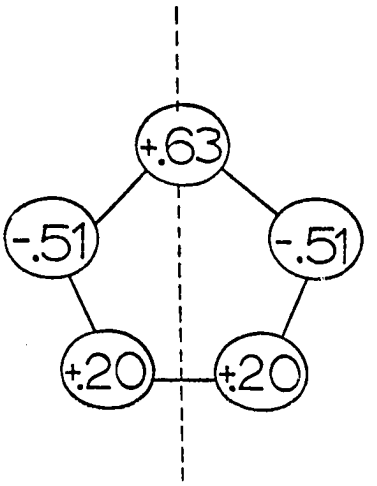
Figure 1. Different representations of the two forms of puckered cyclopentane.

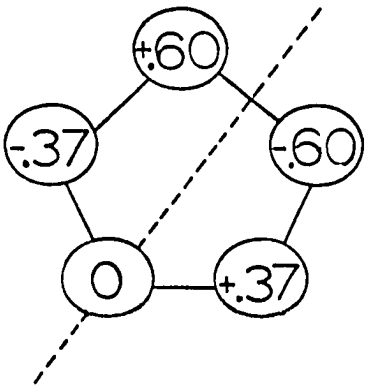












Envelope

Half-chair

mole) being more than compensated for by the considerable drop in eclipsing strain (7.8 kcal./mole) (5). The over-all reduction in strain, estimated (6) at about 3.6 kcal./mole, brings the calculated residual strain in cyclopentane down to 10.4 kcal./mole.

The puckering of cyclopentane has been detected experimentally by several methods, of which the earliest (7) was based on entropy measurements, and the most recent (8) on electron diffraction. Recent calculations have shown (6, 9) that the energy minimum of the cyclopentane molecule is attained when one carbon atom twists out of the plane by 0.5Å. This puckering is not fixed but rotates around the ring by a successive up and down motion of the five methylene groups in what has been termed "pseudorotation" (5). The nonplanar cyclopentane cannot be represented by a single structure. In the course of this pseudorotation the internal energy of the molecule changes by less than RT (600 cal./mole at room temperature), so that, unlike the chair form of cyclohexane, no definite energy minima and maxima come into evidence.

Of the various puckered forms of the cyclopentane ring the "envelope" form (C_s) and the "half-chair" form (C_2) have the greater symmetry and do not vary greatly in their energy levels. Representations of these forms are given in Figure 1. One carbon atom projects out of the plane of the other four in the envelope form, whereas in the half-chair form the three neighboring carbon atoms lie in one plane, while the other two are twisted such that one lies above and the other below this plane. The numbers in the third diagram indicate the displacement in angstroms of the atoms above or below the plane of the paper (10). From the diagram three types of bonds can be recognized 1.) the classical axial (a) and

equatorial (e) bonds found in cyclohexane, 2.) the quasiaxial (a') and quasiequatorial (e') bonds, and 3.) the so-called bisectional bonds (b) which take up a position between the axial and equatorial bonds and form an angle of $54^{o}44'$ with the plane of the ring (4).

Whereas the nonsubstituted cyclopentane has free pseudorotation, either the envelope or half-chair conformation is stabilized by replacement of a hydrogen atom with a bulkier substituent. The energy barrier for pseudorotation then is not zero. Infrared spectra of halocyclopentenes indicated pseudorotation was not present in this series (11). The half-chair form of the five membered ring is preferred by molecules whose energy barrier between neighboring bonds is lowered by substitution. In cyclopentanone, methylenecyclopentane, and heterocyclic analogs of cyclopentane, such as tetrahydrofuran, pyrrolidine and tetrahydrothiophene, two pairs of hydrogen-hydrogen eclipsings are removed. These molecules are most stable in the half-chair form with the sp^2 carbon or heteroatom located on the axis of symmetry. The conformations of these compounds were confirmed by calculations of the enthalpy and free-energy change in the cyclopentanone --- cyclopentanone cyanohydrin equilibrium (6, 12). From the dissociation constants of the cyanohydrins of a number of methyl-substituted cyclopentanones it has been concluded (13) that a substituted cyclopentanone assumes a half-chair conformation, but passes to an envelope conformation on further methyl substitution.

Measurements of the infrared carbonyl stretching frequencies and dipole moments in 2-halocyclopentanones indicate an angle of 77^{o} between the carbonyl and C-X bond. This is very close to the calculated 78^{o} for the half-chair conformation, but incompatible with the 94^{o} angle expected

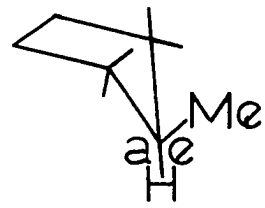
from the envelope or the 60° angle expected in a planar molecule (9). Cyclopentanone was calculated as 1.9 kcal./mole lower in energy than cyclopentane even with consideration of the greater angle strain caused by the carbonyl group (6).

Pitzer in 1948 proposed a planar arrangement for the carbon atoms of cyclopentene on the basis of thermodynamic investigations and infrared and Raman spectra. He was also able to show from calculations of the strain energy of various possible molecular models, that a deviation from the planar structure of 0.3Å by the carbon atom lying transannular to the double bond is possible without any noticeable change in the energy (14). It has also been shown with the aid of NMR spectroscopy and microwave spectra that cyclopentene is bent with the 4-carbon atom being out of the plane and the dihedral angle between the two skeletal planes being 22°16' (4, 15).

Models suggest that cyclopentene and cyclopentene oxide are more strained than their cyclohexyl analogs. Nevertheless hydrogenation of cyclopentene is 1.66 kcal./mole less exothermic than hydrogenation of cyclohexene (16). Thus, the greater angle strain in the cyclopentenes is more than offset by the greater residual eclipsing strain in the cyclopentane hydrogenation products. Cyclopentene is less favorable by approximately 5 kcal./mole than cyclohexene using heats of combustion measurements on the saturated ring compounds. Another manifestation of the phenomenon is the fact that cyclohexene oxide is less readily formed from the trans-chlorohydrin than is cyclopentene oxide but, on the other hand, is more readily opened by hydrogen chloride or potassium thiocyanate (3). Similar investigations have also been carried out for mono- and dimethy-

ated cyclopentenes (4), but these results similarly do not permit an unequivocal conclusion concerning the detailed structure of the carbon skeleton.

The envelope conformation is formed because there is a reduction in the Pitzer strain of the entire system when one carbon atom twists out of the plane of the five-membered ring. Thus, any substituent which increases the energy barrier between two neighboring bonds will force the ring into the envelope form. Methylcyclopentane can exist preferably in conforma-

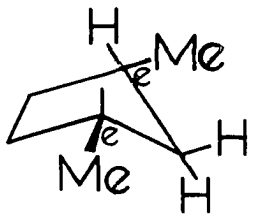


(2)

tion 2, because the interactions between the methyl group and the neighboring hydrogen atoms are lowest in this conformation. Evidence for this is that the difference in heats of combustion of cyclopentane and methylcyclopentane is only a little greater than the corresponding difference between those of cyclohexane and methylcyclohexane. The envelope conformation 2 is stabilized by 0.9 kcal./mole compared to the half-chair form, in good agreement with the value of 0.75 kcal./mole obtained from entropy measurements (4). The substituent in the half-chair form would have only one side corresponding to a staggered enthane while the other side would remain mostly in the eclipsed arrangement.

A more convincing example of the envelope conformation is presented by the 1,3-dimethylcyclopentanes. The cis-isomer is thermochemically

more stable by 0.53 kcal./mole than is the trans-isomer, as determined from heats of formation (17). This finding is not reasonable on the basis of a planar model, but can be readily explained if the cis-isomer is in a diequatorially substituted envelope conformation 3. In the case



(3)

of the trans-isomer one methyl group must assume the unfavorable axial position. The difference in enthalpy between cis- and trans-1,3-dimethylcyclopentane is, however, considerably less than the difference between the corresponding cyclohexanes (1.96 kcal./mole), suggesting that in cyclopentane the staggering is not so pronounced as in cyclohexane. Angle strain would become excessive if the staggering were the same in the two systems. The difference in enthalpy between cis- and trans-1,2-dimethylcyclopentane (1.71 kcal./mole) is also less than the corresponding difference for the cyclohexane analogs (1.87 kcal./mole) (3). The contrary should occur if the cis-methyl groups were eclipsed, as they would be if the ring were planar.

Infrared studies of cyclopentanol disclosed the presence of two C-(OH) stretching vibrations in the region of 1065 and 996 cm^{-1}, which were assigned to the equatorial or quasi-equatorial positions on the one hand and to the bisectional positions on the other. This leads to the conclusion that cyclopentanol exists in two conformations. 2-Alkyl-

substituted cyclopentanols, however, appear to prefer the envelope form (18). The change in infrared spectrum of 1,1,2-trichlorocyclopentane with temperature and state of aggregation has also been interpreted in terms of two distinct contributing conformations in equilibrium with each other (19). cis-Cyclopentane-1,2-diol in dilute carbon tetrachloride solution shows intramolecular hydrogen bonding, the separation of the unbonded and bonded hydroxyl stretching frequencies being 61 $cm.^{-1}$ (20). The corresponding separation in trans-cyclohexane-1,2-diol (torsional angle 60°) is 32 $cm.^{-1}$, whereas in a variety of bicyclo [2,2.1]-heptane-cis-2,3-diols (torsional angle 0°) the separation is 100 $cm.^{-1}$. It may thus be estimated that the torsional angle in cis-cyclopentane-1,2-diol is of the order of 20-30°. The predicted torsional angle for cis-1,2-substituents may be as low as 0° (in the envelope form, at the carbon atoms distant from the flap) or as high as 48° (in the half-chair form, at the carbon atoms involved in maximum staggering). The minimum torsional angle for trans-1,2-substituents is 72°, which is too large for intramolecular hydrogen bonding in diols; in fact, trans-cyclopentane-1,2-diol shows no intramolecular hydrogen bond in the infrared (3).

Chemical methods in conformational analysis have been used successfully on systems of condensed cyclohexane rings, as their rigid structure usually permits only one conformation. In compounds in which a number of conformations are possible, these methods do not always produce unequivocal results. Kinetic conformational analyses, which employ reaction rates to ascertain conformations when used in conjunction with product analysis studies and thermodynamic equilibrium states between sterioisomeric com-

pounds give a good indication of the steric requirements within a given molecule.

The distinctive chemical properties of cyclopentyl systems compared to cyclohexyl or acyclic systems may usually be explained in terms of the fact that even in the puckered form there is substantial bond eclipsing giving rise to torsional strain, in contrast to the situation in cyclohexane or open chain derivatives which tend to be nearly perfectly staggered.

Reactions of cyclopentane derivatives in which there is relief of torsional strain and accompanying angle strain (I-strain) will tend to be abnormally fast, whereas reactions in which strain is built up in a cyclopentanoid system will be abnormally slow. Among the former are the solvolysis of 1-methylcycloalkyl chlorides in 80% ethanol, the acetolysis of cycloalkyl tosylates in acetic acid, and the hydrolysis of cycloalkyl bromides in 41% dioxane. The ratios of rate constants of the cyclopentyl:acyclic:cyclohexyl compounds are 43.7 : 1 : 0.35, 10.5 : 1 : 0.75, and 13.3 : 1 : 0.45 respectively (3). In the S_N2 reaction of cycloalkyl bromides with iodide ion the ratios of rate constants of cyclopentyl: acyclic:cyclohexyl are 1.2 : 1 : 0.0015. In this case a factor is at work which counteracts the expected I-strain acceleration in the cyclopentyl bromide and reinforces the retardation in the six-membered ring. It has been suggested (21) that the factor which slows down S_N2 reactions in ring systems as compared to acyclic ones is interference of the ring structure with the optimum bipyramidal transition state, which requires colinearity of the incoming and outgoing groups with the carbon atom at which the reaction occurs. Similarly, the decomposition of the azo-bis-nitriles in

toluene is about 10 times faster for cyclopentane than for cyclohexane, thus the formation of the radical also results in the relief of eclipsing strain in the case of the five-membered ring (22). An example of the second case where I-strain is increased in the cyclopentane system is the sodium borohydride reduction of cycloalkanones. The relative rates of di-n-hexyl ketone, cyclopentanone, acetone, and cyclohexanone are 0.45 : 7.01 : 15.1 : 161. While there is a considerable decrease in angular deformation at the carbonyl of cyclopentanone upon reduction, the increased torsional strain in the product more than outweighs it. In cyclohexanone the eclipsing of the carbonyl by the equatorial hydrogens, a situation unfavorable relative to an open chain, is removed upon reduction to give the staggered alcohol.

A chemical conformational analysis is dependent upon certain assumptions. An example of this is found in the iodine-catalyzed elimination of bromine from trans-1,2-dibromocyclopentane. This E2 reaction goes through a transition state in which the four atoms, Br-C-C-Br, lie in one plane (trans coplanar transition state). An open-chain compound such as 1,2-dibromoethane can readily assume this necessary conformation with relatively unhindered rotation about the C-C bond. The bromine atoms can also achieve this arrangement (trans-diaxial) in trans-1,2-dibromocyclohexane. However, if the substituents are located in the cis-1,2-positions on the cyclohexane ring, a coplanar transition state is not possible and the rate of elimination is much slower. Since this elimination is very rapid with a low activation energy in trans-1,2-dibromocyclopentane (3.9 times that of the corresponding cyclohexyl derivative), the diaxial-trans arrangement of bromine atoms can be approached in the transition state of

the five-membered ring without a great expenditure of energy (4). This is only possible if the cyclopentane ring does not occur in a planar structure, but is in the puckered envelope conformation. The measured dipole moment of trans-1,2-dibromocyclopentane ($\mu = 1.6$) (23) indicates a quasi-axial position of the bromine, whereas the dipole moment of trans-1,2-dibromocyclohexane is between 1.76 and 2.16 D., depending upon the solvent.

The rates of solvolysis in 80% aqueous ethanol of cis- and trans-2-chlorocyclohexyl phenyl sulfide and cis- and trans-2-chlorocyclopentyl phenyl sulfide were studied by Goering and Howe (24). They observed for the corresponding pairs of isomers values of k_{trans}/k_{cis} were only 2.5 times larger for the cyclohexyl system than for the cyclopentyl system. The large values of k_{trans}/k_{cis} (10^6) for each system show that the trans-isomers solvolyze exclusively by an anchimerically assisted process. Since participation by a beta-sulfide group is largely or completely precluded if the C-Cl and C-S bonds cannot become coplanar, the large anchimeric acceleration observed suggests again that not much strain is required for cyclopentane to assume a conformation in which the adjacent trans-bonds are coplanar.

The solvolysis of various alkylated cyclopentanols was studied by Hückel and coworkers (25, 26, 27, 28). The results of solvolyses of these compounds are tabulated in Tables 1 and 2. Following is a brief summary of the results that were obtained. The solvolyses of the cyclopentyl p-toluenesulfonates are significantly faster than the analogous cyclohexyl compounds in all solvents studied. The methanolysis of cyclopentyl tosylate itself affords nearly exclusively ether resulting from

Table 1. Kinetics of the ethanolysis of cyclic p-toluenesulfonates.

p-Toluenesulfonate	Temp.	$\frac{k_1 cis}{k_1 trans} \times 10^6$	$\frac{E_{act} cis}{E_{act} trans}$
3-i-Propylcyclopentanol	30° 40°	7.20/ 5.66 22.81/19.35	21.6/23.1
3-i-Propylcyclohexanol	50° 60°	0.71/ 2.83 2.54/ 9.90	27.7/25.5
2-i-Propylcyclopentanol	40°	77.00/11.00	
2-i-Propylcyclohexanol	40°	22.10/ 0.33	
2-Cyclopentylcyclopentanol	40°	61.00/ 9.00	
2-Cyclohexylcyclohexanol	40°	30.60/ 0.37	
Cyclopentanol	40° 50°	16.60 50.00	22.7
Diethylcarbinol	40°	4.38	23.2

displacement, whereas cyclohexyl tosylate gives mainly elimination to form the olefin. A 2-alkyl substituent cis to the toluenesulfonate (tosylate) group increases the reaction rate over the unsubstituted compound by a factor of 3 to 5, whereas a trans-2-substituent decreases the rate by one-half to one-quarter.

The rate ratio cis/trans for the solvolysis of the 2-substituted cyclohexane compounds amounts to about 100. The axial p-toluenesulfonate group of the cis-compound is solvolyzed more rapidly due to steric acceleration from eclipsing, less hindered attack from the rear of an axial substituent, and possible participation of the neighboring hydrogen (4). In the case of the 2-alkyl cyclopentyl tosylates, the ratio between the

Table 2. Kinetics and product analysis from the methanolysis of cyclic p-toluenesulfonates.

p-Toluenesulfonate	Temp.	$k_1 \times 10^6$	E_{act}	Ether / olefin	1-Olefin / 3-olefin
cis-2-Methylcyclopentanol	30° 40°	22.2 70.0		60/40	92/8
trans-2-Methylcyclopentanol	30° 40°	4.4 12.8		75/25	100/0
cis-2-Methylcyclohexanol	40°	30.4	24.4		
trans-2-Methylcyclohexanol	60°	4.45	28.2		
cis-2-i-Propylcyclopentanol	40°	264.0		36/64	63/2[a]
trans-2-i-Propylcyclopentanol	50°	115.0		53/47	68/7[a]
cis-2-i-Propylcyclohexanol	50°	331.0			
trans-2-i-Propylcyclohexanol	60°	16.4			
Cyclopentanol	40°	55.3	22.1	91/9	
Cyclohexanol	50°	4.78		29/71	
Diethylcarbinol				88/12	
trans-2-Cyclopentylcyclopentanol	50°	110.0			
trans-2-Cyclohexylcyclohexanol	60°	23.0			
cis-3-i-Propylcyclopentanol				93/7	50/50[b]
trans-3-i-Propylcyclopentanol				94/6	55/45[b]

[a]Remaining per cent is exo-olefin.

[b]Ratio of 3-olefin to 4-olefin.

cis- and trans-compound lies between 7 and 10. This suggests the absence of strong eclipsing effects in the cis-isomer as well as the absence of

neighboring hydrogen participation. The small difference may be explained on conformational grounds by assuming a puckered chair gives rise to a quasi-axial position of the tosylate group. The trans-2-alkylcyclopentyl p-toluenesulfonates react 30-40 times faster than the analogous cyclohexane compounds; but the activation energy is about 3 kcal. lower. The cis-2-alkylcyclopentyl p-toluenesulfonates have the same activation energies as the corresponding cyclohexyl compounds but react 3-4 times more rapidly. The substitution and elimination reactions occurring concurrently during the solvolysis of the tosylates is shifted in favor of the substitution reaction for the trans-2-alkylcyclopentane compounds. Yet considerable amounts (between 30% and 70%) of unsaturated hydrocarbon are still formed. The explanation could be found in the fact that, as a result of the quasi-equatorial position of the substituents on the cyclopentane ring in comparison to the equatorial position on the cyclohexane ring, backside attack of the solvent is favored in an S_N2 reaction with Walden inversion.

Brown and Chloupek (29) have also observed the marked increases in ethanolysis rates by the addition of a methyl group in the 2-position of a series of 1-chloro-1-methylcyclopentanes. In contrast to the 2-substituted cyclopentyl derivatives, Lillien (30) has found the relative rates of acetolysis of trans- and cis-3-t-butylcyclopentyl p-toluenesulfonates to be 1.06 : 1.00 respectively. He attributes this lack of solvolytic discrimination to the substituents in both isomers assuming diequatorial positions; the half-chair conformation for the trans-isomer and the envelope conformation for the cis-isomer.

Bordwell and coworkers (31) have studied the base catalyzed eliminations in the 2-p-tolylsulfonylcycloalkyl p-toluenesulfonate system. They

observed that trans-elimination in the cyclopentyl system is favored over that in the cyclohexyl series by a factor of 3, whereas factors of 435 favoring trans over cis elimination in the cyclohexyl series and 20 favoring trans over cis elimination in the cyclopentyl series were noted. The data indicate that it is easier to introduce a double bond into a five-membered ring than into a six-membered ring and that the cis-cyclohexyl compound, relative to the trans-isomer, can acquire a planar four-centered transition state with greater ease than in the cyclopentane series.

Qualitative considerations of addition-elimination reactions from a quantum mechanical-conformational point of view indicate that when an anti-elimination is impossible the next most favorable transition state for reaction involves a syn-cis (syn-periplanar) arrangement of groups (3). Experimentally it has been found that the ratio of elimination rates with potassium t-butoxide of the cis- and trans-2-phenylcyclopentyl p-toluenesulfonates is only 9.1 (32, 33), whereas the corresponding ratio for the 2-phenylcyclohexyl compounds was extremely high ($>10^4$). It has been suggested that a plot of the rate of elimination vs. the dihedral angle, ϕ, between the hydrogen and the departing anion will show maxima at both 0° and 180° and a minimum at 90° (34). This reflects the fact that coplanar transition states, whether cis or trans, are vastly preferable to noncoplanar ones. This relationship could be used in conjunction with the measured rates of eliminations to determine qualitatively the dihedral angle and thus the amount of puckering in substituted cyclic systems.

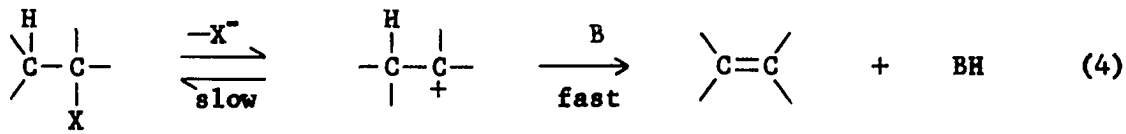
Experimental data for other reactions is too limited to be used for conformational analysis with unequivocal value. This is especially true

for equilibrium measurements, a method used with success to determine relative thermodynamic stabilities of cyclohexanols. In the few examples of the cyclopentyl system studied, the equilibrium favors the trans-compound. Reduction of 2-alkyl-ketones with sodium in alcohol leads predominately to the trans-alcohol and reduction of ketones with lithium aluminum hydride also yields the thermodynamically more stable trans-alcohols in greater amounts (4).

Elimination Reactions

Beta eliminations are processes in which two atoms or groups are removed from adjacent carbon atoms to form a multiple bond. Three principal mechanisms for beta eliminations have been recognized by Hughes and Ingold, The terms E1, E2 and E1cB were originated by Ingold (35) for these reactions. The difference between these mechanisms lies in the relative extent of C-H and C-X bond breaking in the rate determining step.

The E1 (unimolecular) beta elimination mechanism discovered by Hughes in 1935 (36) involves the heterolytic cleavage of the C-X bond to form a carbonium ion intermediate in the rate determining step, which then loses a beta hydrogen to solvent or base to form the unsaturated product. The

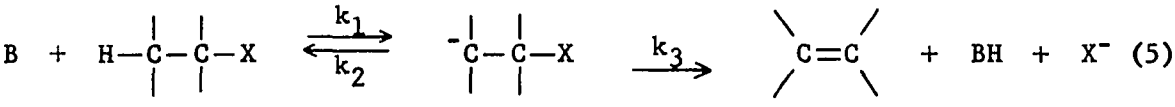


(4)

reaction is first order in substrate and occurs only if a stable carbonium ion can be formed (37). This mechanism is characterized by a) acceleration in polar solvents and addition of salts, b) acceleration by

branching at the beta-carbon (Saytzeff product formation) c) unfavorable competition with S_N1, d) olefin composition and the ratio of k_{E1}/k_{S_N1} being independent of leaving group, e) low C-H and high C-X isotope effects, f) rearranged products characteristic of carbonium ions and g) reversibility of the reactions (38).

The ElcB (carbanion) mechanism envisions base abstraction of the beta-hydrogen in a reversible step to give an anion which in a subsequent step forms an olefin with the removal of the leaving group. Factors



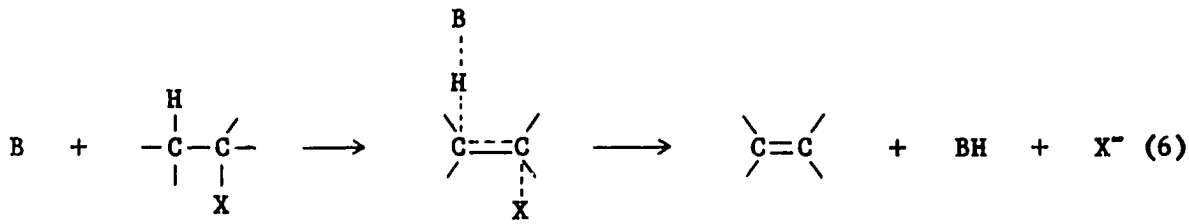
(5)

which favor an ElcB mechanism are a poor leaving group, good stabilization of the carbanion by alpha and beta substituents, and conformational effects which would prevent an E2 elimination from attaining a preferred co-planar transition state (39).

Although there is numerous evidence for an ElcB mechanism from deuterium exchange studies with solvent (39, 40, 41) and systems whose ratio of $k_{\underline{trans}\ elim.}/k_{\underline{cis}\ elim.}$ is small, (42, 43, 44, 45, 46, 47, 31) its existence has not as yet been unambiguously shown. Ideally, the carbanion intermediate could be shown by deuterium exchange with solvent in the reversible step, though this wouldn't be a necessary condition if $k_3 > k_2$. The latter is generally the case for saturated systems. Even if deuterium exchange does occur, this may be an irrelevant side reaction and not a true intermediate in the elimination reaction (48). Experimental criteria which should distinguish the ElcB from the E2 mechanism are

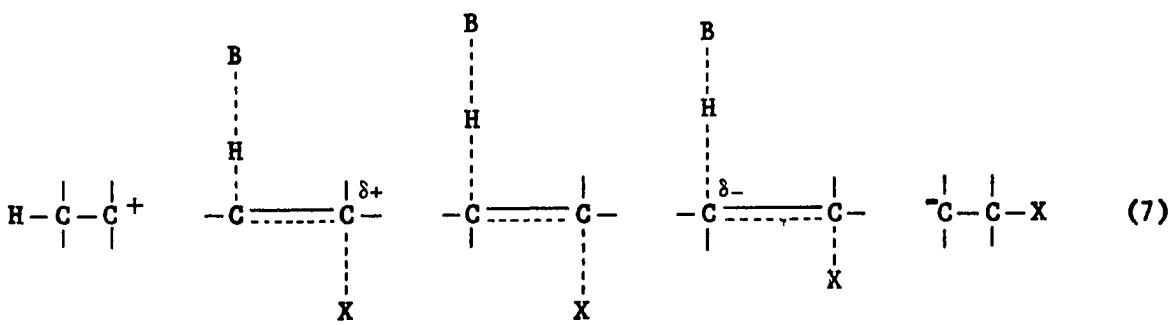
specific base catalysis and/or kinetic isotope effects (38).

In the E2 (bimolecular) elimination mechanism first recognized by Ingold in 1927 (49), the beta proton and the leaving group are lost simultaneously under the influence of base.



(6)

The E2 mechanism in its current interpretation (50) is no longer restricted to the completely concerted transition state, but encompasses the range from the "nearly E1" transition state (the C-X bond breaking has progressed much farther than the C-H bond breaking) to the "nearly E1cB" transition state (the C-H bond breaking is much more important than the C-X bond breaking). Between these extremes, a gradual change through an infinite number of intermediate possibilities can be visualized. At the central position, C-X and C-H rupture have made equal progress with a large degree of double bond character possible.



(7)

E1 "Nearly E1" "Central E2" "Nearly E1cB" E1cB

Even this broad mechanism scheme is not adequate to encompass all the data, as a diversity of the "central" transition state is also conceivable. The fractional degrees of C-X and C-H bond breaking are equal, but this fraction can vary from nearly zero to nearly one. Moreover, the degree of double bond character in the transition state need not equal the degree of C-H (C-X) rupture, but can also vary from zero to the per cent of C-H (C-X) bond breaking.

Most of the data on E2 reactions can be interpreted on the basis of changes in the relative timing of bond breaking in the transition state (50). Changes in the structure of the substrate and conditions of the reaction which tend to shift the transition state toward "nearly E1" are 1.) introduction of an alpha-alkyl or aryl substituent, 2.) introduction of a better leaving group, 3.) introduction of a beta-alkyl substituent, and 4.) change to a more polar solvent; whereas changes that tend to shift the transition state toward "E1cB like" are 1.) introduction of a greater electron-attracting leaving group, 2.) introduction of a beta-aryl substituent, 3.) introduction of an electron-attracting beta-substituent, and 4.) change to a stronger base.

There are certain criteria of the E2 mechanism which appear in the form of rate coefficients or as relative yields of products. These criteria help determine the relative importance, extent and timing of C-H and C-X bond breaking and/or C=C formation in the transition state.

X isotope effects: The lighter isotope reacts faster than the heavier one, this ratio being a direct measurement of the amount of C-X bond breaking. The isotope effect depends only on the extent to which the composite force constant of the C-X bond decreases in going from the

initial state to the transition state. E1 eliminations have the maximum X isotope effect. Nitrogen and sulfur in the onium ions have been the only X isotope effects measured thus far in elimination reactions. For the 2-phenylethyl system the S_{32}/S_{34} effect in the sulfonium ion was 10% of the maximum (51) and N_{14}/N_{15} was shown to be 30% of the maximum (52, 53).

H isotope effects: The maximum deuterium isotope effect would be expected when the beta-hydrogen is fifty per cent transferred to the base (54,55), and the k_H/k_D ratio gradually decreases as the hydrogen becomes more or less transferred. If no C-H bond breaking occurs or if a carbanion intermediate is formed (E1cB) in the rate determining step then k_H/k_D would equal one. Recently, though, it has been pointed out that deuterium isotope effects may be quite ambiguous (56).

Recently Thornton (57) has measured $k_{OD^-\text{-}D_2O}/k_{OH^-\text{-}H_2O}$ solvent isotope effects of 1.79 and 1.57 for $C_6H_5CH_2CH_2\overset{+}{N}(CH_3)_3Br^-$ and $C_6H_5CH_2CH_2\overset{+}{S}(CH_3)_2Br^-$. The greater the isotope rate ratio the more tightly the beta proton is attached to the base in the transition state. This evidence supplements the k_H/k_D measurements and gives a good indication as to the extent of beta-hydrogen transfer in the transition state.

Stereoelectric preference for trans-elimination: It is known (58, 59) that a trans-elimination with an antiperiplanar transition state is favored for an E2 reaction. This is reflected both in the relative rates of trans- and cis-elimination (60, 61, 41) and the identity of the product olefins formed from diasterioisomers (62, 63). Recently facile cis-eliminations have been observed in systems containing a hydrogen which is acidified by an adjacent electron-withdrawing group or in systems which

have difficulty in attaining an anticoplanar transition state because of steric requirements (64, 65, 66, 33, 42, 46). Sicher (67) has proposed a cis-elimination in an acyclic system to account for the preponderance of

Table 3. Effect of dihedral angle on the relative rates of cis- and trans-elimination.

Compound	Temp.	$\frac{k_{trans\text{-}elim.}}{k_{cis\text{-}elim.}}$	dihedral angle cis	dihedral angle trans
β-Hexachlorobenzene[a]	30°	2×10^4	60°	180°
2-Phenylcyclohexyl p-toluenesulfonate[b]	50°	10^4	60°	180°
2-Phenylcyclopentyl p-toluenesulfonate[b]	50°	9.1	20°c	150°c
2-Phenylcyclobutyl p-toluenesulfonate[d]	50°	2.6	10°c	140°c
11,12-Dichloro-9,10-dihydro-9,10-ethanoanthracene[e]	110°	1/7.8	0°	110°
Endo-2,3-dibromonorbornane[f,g]	87°	1/31.0	0°	120°
Endo-2,3-dichloronorbornane[f,g]	110°	1/80.0	0°	120°
Exo-2,3-dibromonorbornane[f,g]	87°	1/86.0	0°	120°

[a]Ref. (68), β-benzenehexachloride.

[b]Ref. (33).

[c]Approximate angle in puckered form established from Dreiding models.

[d]C. Hendrickson, Dept. of Chemistry, Iowa State University, Ames, Iowa. Eliminations of Cyclobutyl compounds. Private communication. 1965.

[e]Ref. (42).

[f]Ref. (69).

[g]Ref. (70).

cis- over trans-olefin formed in eliminations giving Hofmann products.

DePuy (34) and coworkers have pointed out that the ease of E2 eliminations may vary with the dihedral angle between H and X. A plot of the rate of elimination of a given system versus the dihedral angle between the leaving group and beta proton is predicted to show a maximum at both 0° (cis coplanar) and 180° (trans anticoplanar) and a minimum at 90°. Elimination transition states in which H and X cannot assume a coplanar or anticoplanar arrangement are much slower and may proceed by an "extreme" E1 or E1cB mechanism (See Table 3).

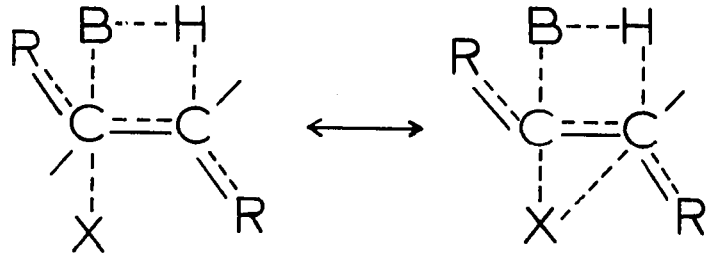
Eclipsing effect: As a saturated system passes into a beta-elimination transition state, substituents on the alpha and beta carbons destined to be cis in the eventual olefin are brought closer together. This degree of eclipse will be directly proportional to the double bond character in the transition state and this in turn will help determine the free energy and therefore the elimination rate (71). Eclipsing effects can be thus assessed in favorable cases from the relative rates of elimination of threo and erythro diastereomers, or from the proportions of cis and trans olefins formed from a substrate with two beta-hydrogens (72,73).

Effects of beta-substituents: a) Beta-aryl substituents help to stabilize a negative charge and should thereby accelerate eliminations occurring in the central and nearly E1cB regions. From measurements on the elimination rates of compounds having meta and para substituted beta-aryl groups, the Hammett rho value can be evaluated. This gives a measure of the negative charge located on the beta-carbon atom in the transition state. b) Beta-halogen atoms have a strong stabilizing influence on a developing negative charge, weak stabilizing effect on a developing double

bond and an unfavorable effect on alpha carbonium ion character. One would predict strong acceleration in reaction rate for a nearly carbanion reaction, slight acceleration in the central region and retardation of "nearly E1" reactions. c) Beta-alkyl groups would decelerate reactions on the "nearly E1cB" side due to the unfavorable inductive effect on the beta-negative charge. For fully synchronous reactions, the stabilizing effect of alkyl groups on adjacent ethylenic linkages should cause an increase in rate, and "nearly E1" reactions should be accelerated by the beta-inductive effect of the alkyl group.

Another method that has been recently used for the determination of the amount of C-X bond breakage in the transition state is the Hammett rho value for m and p-substituted benzenesulfonates. The rho value becomes more positive as this leaving group's separation from the alpha carbon atom in the transition state increases. Colter has measured rho values of 1.51 and 1.35 for the reactions of 2-methyl-3-pentylarenesulfonate and 2-pentylarenesulfonate respectively (74). Also from the product ratios in these systems it appears that the ease of heterolysis of the C-O bond in the transition state is more sensitive to electronic influences of the leaving group than to the acidifying effect on the β-hydrogens (75).

Csapilla (76) has recently proposed a new mechanistic interpretation of E2 reactions. He proposes a transition state in which the base nucleophilically binds to the alpha-carbon at the same time it extracts a proton. This intermediate was proposed primarily to explain differences between thermodynamic and kinetic basicity. However, Csapilla also ex-



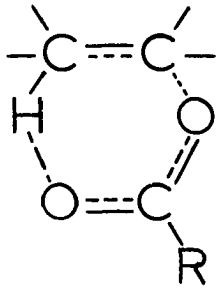
(8)

plained by this mechanism the favoring of trans-elimination over cis-elimination, substituent and isotope effects, orientation, and competition between S_N2 and E2 reactions.

Data for numerous E2 reactions have been correlated by the above mentioned criteria to determine the relative extents and timing of C-H and C-X bond breaking and C=C bond formation in the transition state (77, 32, 50). Recently the ratios of product olefins were used in the 2-substituted butyl and pentyl systems to substantiate the predicted effects resulting from changes in the leaving group (78) and changes in the base/solvent system (79, 80) on the E2 transition state. The relative position in the E2 reaction spectrum of transition states may be further correlated by other factors. Preliminary investigation (81, 82) indicates that the t-butoxide/ethoxide and bromide/tosylate rate ratios may be important in determining the relative position of a compound in this spectrum.

In gas-phase pyrolysis reactions it is possible to investigate the behavior of a single molecule, uninfluenced by the presence of the remainder of the system. The effect of substitution in a parent molecule

can be studied without the usual complications arising from solvent effects. Pyrolytic eliminations have been extensively investigated using four groups of compounds---esters, xanthates, amine oxides, halides---and to a lesser extent using vinyl ethers, amides, carbonates, sulfoxides and alcohols. The predominant steric course of this reaction has been shown to be cis by a number of investigators (83). The transition state involves a cyclic intermediate in which the beta-hydrogen is abstracted by the carbonyl oxygen of the ester as the C-O bond is breaking and some double-bond character is developing between the carbon atoms. This transition state is consistent with the observed first order kinetics, the



(9)

large negative entropy of activation, the absence of induction periods and of any effect by free radical inhibitors, and the identity of the product olefins formed (84). Isotope effects indicate a large amount of carbon-hydrogen bond breaking in the transition state (83), whereas the rho value (0.3) for the 2-arylethylacetates at 377° indicates a small amount of negative charge buildup on the beta-carbon atom (85). A rho value of -0.66 measured for the pyrolysis of the 1-arylethylacetates at 327° (following σ^+ relationship) (85) and a rate acceleration by electronegatively substituted aryl esters (86) indicates a small degree of charge separation on the alpha-carbon. This is in agreement with the

relative pyrolytic rates ($3^{o} > 2^{o} > 1^{o}$) of substituted esters (83).

In addition to competing radical reactions observed in some cases, recent results indicate the possibility of heterolytic cleavage in the gas-phase---particularly in the case of alkyl halides (87, 88, 71). Also in many cases small amounts of products obtainable from trans-elimination are observed, indicating the pyrolysis reaction is not mechanistically homogeneous. Several investigators have suggested that trans-elimination may be a direct consequence of conformational effects, involving elimination of diequatorial substituents in cyclic systems (89).

The direction of elimination in esters containing two beta-hydrogen atoms is generally governed by four factors. These are (a) the number of available hydrogen atoms on each adjacent carbon atom (statistical effect), (b) the repulsive interactions of groups in the transition state (steric effects), (c) the relative stability of the olefinic products formed (thermodynamic effects), and (d) the relative acidity of the hydrogen atom removed---this may become important in esters with especially activated hydrogen atoms (83).

In cyclic systems it becomes more difficult to treat the product distribution in terms of separate steric, statistical, and thermodynamic effects, as conformational effects may become important. The pyrolysis of 1-methylcyclohexyl acetate at 400^{o} gave 74% of 1-methylcyclohexene and 26% methylenecyclohexane. The preponderance of the internal olefin has been ascribed to the well-known greater stability of the endo-olefin in the cyclohexane series (90) and the fact that pyrolytic eliminations have transition states with appreciable double bond character (83). The pyrolysis of dimethyl (1-methylcyclohexyl) amine oxide, however, gives a

mixture of 97% methylenecyclohexane and only 3% 1-methylcyclohexene. The difference between the amine oxide and acetate pyrolysis was explained by the greater flexibility in the transition state of the acetate due to the extra atom involved, thus allowing the elimination to take place directly from the chair form of the cyclohexane ring. In contrast, the elimination from the amine oxide demands eclipsing; hence elimination into the ring, via the boat form, is unfavorable (83). 1-Methylcyclopentyl acetate gives 85% 1-methylcyclopentene and 15% methylenecyclopentene upon pyrolysis, indicating the dihedral angle between the hydrogen and the acetate is less in the five-membered ring than in the six-membered ring and the greater stability of the endocyclic double bond due to reduction of non-bonded interactions in the cyclopentane ring. In contrast to the cyclohexyl system, dimethyl (1-methylcyclopentyl) amine oxide upon pyrolysis gives 97% of the endo-olefin (1-methylcyclopentene), as little additional activation energy is required since the substituents are already approximately eclipsed.

It was shown that there were no conformational effects in the pyrolysis of cis- and trans-1-methyl-4-t-butylcyclohexyl acetates, since they gave the same exo/endo product ratio as was found in the pyrolysis of 1-methylcyclohexyl acetate. The relative rate studies on these acetates and on cis- and trans-4-t-butylcyclohexyl acetate indicated the ease of pyrolysis depends mainly on the ground state energy of the acetates, since in the first case the equatorial ester undergoes elimination more readily (1.43 : 1) while the axial ester is the more reactive (1.69 : 1) of the 4-t-butylcyclohexyl acetates (91).

Extensive work has been published on the pyrolyses of alicylic compounds (38, 83, 89) and the more highly substituted olefin usually predominates by a small amount in the absence of conformational effects. Conformational effects, though, should be very small at the high temperatures used in pyrolysis reactions; in fact in reactions involving the cyclohexane ring both the chair-boat and chair-chair equilibria should be considerably displaced in favor of their less stable forms.

RESULTS AND DISCUSSION

Synthetic

The t-butylcyclopentyl system was the first system undertaken for the study of elimination reactions. It was thought that the bulky tertiary-butyl group would cause a large puckering of the cyclopentane ring and the ring would be "locked" in an envelope or half-chair conformation, analogous to the t-butylcyclohexyl compounds studied (92, 93). A comparison of this system with the unsubstituted cyclopentyl compounds and the previously studied phenyl-, methyl- and i-propylcyclopentyl compounds should give a good indication of the steric requirements of a t-butyl group and its effect on the conformation of the five-membered ring. This should appear in the form of differing product ratios and relative rate differences using a number of chemical reactions.

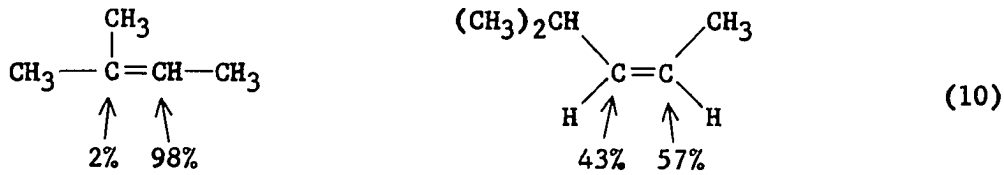
The syntheses and separations of the isomeric cis- and trans-2- and 3-t-butylcyclopentanols proved difficult. The attempted preparation of 1-t-butylcyclopentanol by the addition of cyclopentanone to t-butyl magnesium chloride resulted in none of the desired product. The side reactions involved (due to the bulk and bascity of the Grignard reagent) are probably reduction of cyclopentanone to cyclopentanol and condensation reactions of cyclopentanone. Similarly, it has been reported (94) that synthesis of 1-iso-propylcyclopentanol in this manner proceeds in only 3.6 per cent yield. Treatment of cyclopentanone with t-butyl lithium, however, produced 1-t-butylcyclopentanol in 14 per cent yield. The less basic t-butyl lithium, relative to the Grignard reaction, decreases

the amount of condensation products formed in favor of nucleophilic attack of the carbonyl group. Catalytic dehydration with p-toluenesulfonic acid gave 1-t-butylcyclopentene. Hydroboration of this olefin should stereoselectively yield only trans-2-t-butylcyclopentanol. However, the cost and the difficulty in preparing t-butyl lithium coupled with the very low yield of the first reaction, make this method unfeasible for the preparation of the trans-2-alcohol in large quantities.

Another stereoselective synthesis for the trans-2-t-butylcyclopentanol was attempted by treating cyclopentene oxide with t-butyl lithium. It has been shown (95) that the epoxide ring-opening occurs by backside attack of the organo-lithium compound to give the trans-alcohol. The epoxidation of cyclopentene with m-chloroperbenzoic acid gave cyclopentene oxide in 70 per cent yield. Treatment of the epoxide with t-butyl lithium resulted in recovered starting material plus a number of compounds---none of which showed an -OH absorption in the infrared.

3-t-Butylcyclopentene was prepared by the reaction of either t-butyl magnesium chloride or t-butyl lithium with 3-chlorocyclopentene (prepared in greater than 90 per cent yield from the low temperature hydrochlorination of cyclopentadiene). Although the yield of the Grignard reaction is low (14-18%), the cost of the starting materials and the ease and brevity of the reaction procedure make this a practical method for a large scale preparation of 3-t-butylcyclopentene. The olefin was separated from the contaminating 3-chlorocyclopentene, cyclopentadiene dimer, and another higher boiling compound---possibly a t-butyl dimer---by careful distillation through a glass helices packed column.

Hydroboration has been shown to give stereospecific cis-addition to a double bond with a preference for the attachment of the boron to the less substituted position 10. There is no significant discrimination



(10)

between the positions of an internal olefin containing groups of markedly different steric requirements. (See above percentages for example in trans-4-methyl-2-pentene.) However, the use of a bulky hydroborating agent (disiamylborane) selectively gives an overwhelming preference for the less-hindered position (97% in trans-4-methyl-2-pentene). The oxidation of organoboranes with alkaline hydrogen peroxide proceeds cleanly and quantitatively, placing a hydroxyl group at the precise position occupied by the boron atom in the organoborane (96).

Hydroboration of 3-t-butylcyclopentene yielded a 65:35 ratio of 2-t-butylcyclopentanol and 3-t-butylcyclopentanol. This ratio of alcohols is exactly the same as Smith (32) observed in the hydroboration of 3-phenylcyclopentene, and is quite different from Brown's result (97) of the hydroboration of 3-methylcyclopentene which gave 55% of the 3-alcohol. These product ratios suggest that the conformation of the cyclopentane ring in the transition state is similar for the phenyl and t-butyl substituted olefins. Separation of the 2- and 3-t-butylcyclopentanols was accomplished using a spinning spiral distillation column with a stainless steel band. Gas phase chromatography (GPC) indicated that the 2-alcohol

consisted of 98% of the trans-isomer, whereas the 3-alcohol contained approximately 84% of the trans-isomer. Smat (89) observed that hydroboration of 1-phenylcyclopentene gave 98% of trans-2-phenylcyclopentanol. Smith (32) reported in the hydroboration of 3-phenylcyclopentene that the 2-alcohols formed consisted of 90% of the trans-isomer and the 3-alcohol contained 60% of the trans-isomer. Brown and Zweifel (97) reported the hydroboration of 3-methylcyclohexene gave 49% of the 2-alcohol and 51% of the 3-alcohol. The 2-methylcyclohexanol consisted of 63% of the trans-isomer, whereas the 3-alcohol contained 48% of the trans-isomer. These results indicate the methyl group in the quasi-equatorial position in 3-methylcyclohexene exhibits little steric influence on the direction of hydroboration; while in the five-membered ring where there is much less puckering and a more bulky 3-substituent in the compounds studied (phenyl or t-butyl), steric factors direct the addition of hydroboration in a trans-direction.

Since Brown and coworkers found the ratio of 2-alcohol to 3-alcohol in the hydroboration of 3-methylcyclopentene (Table 4) to be dependent upon the bulk of the hydroborating agent, it was thought that use of triisopinocampheyldiborane should greatly increase the ratio of 3-alcohol to 2-alcohol in the hydroboration of 3-t-butylcyclopentene. The observed ratio of 2-t-butylcyclopentanol to 3-t-butylcyclopentanol (60:40) for the hydroboration with triisopinocampheyldiborane was only slightly different than that obtained (65:35) using diborane. Thus, the difference in steric interactions in the transition state with a bulky versus a small hydroborating agent is less for the 3-t-butylcyclopentene than for 3-

Table 4. The effect of size of the hydroborating agent upon the alcohol ratio in 3-methylcyclopentene (97, 98).

Hydroborating agent	Per cent 2-methylcyclopentanol	Per cent 3-methylcyclopentanol
Diborane	45	55
Disiamylborane	40	60
Diisopinocampheylborane	30	70

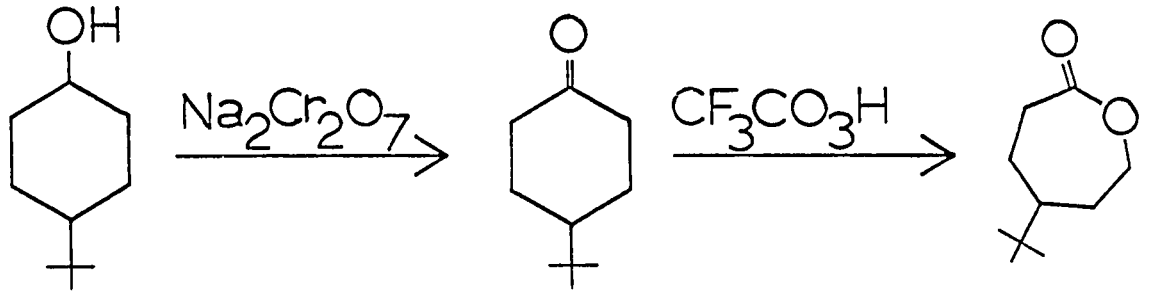
methylcyclopentene. This may be a result of differences in the relative amounts of cis- and trans-isomers of the respective alcohols formed from the two olefins. Since more cis-2- and 3-alcohol is undoubtedly formed from 3-methylcyclopentene and since steric interactions (shown from models) are much more severe in the transition state for the formation of cis-alcohol (particularly in the case of the 2-alcohol), one can rationalize the above results. Using dextrorotatory α-pinene of 17% optical purity, levorotatory trans-2-t-butylcyclopentanol (-1.297°) was formed. The 3-t-butylcyclopentanol formed exhibited no optical rotation, indicating steric interactions upon addition to the 3-position weren't sufficient to cause a distinction between the enantiomorphs. Brown and coworkers (99) determined trans-2-methylcyclopentanol was obtained in 17.5% optical purity from the hydroboration of 3-methylcyclopentene with triisopinocampheyldiborane at 0° for 3 hours.

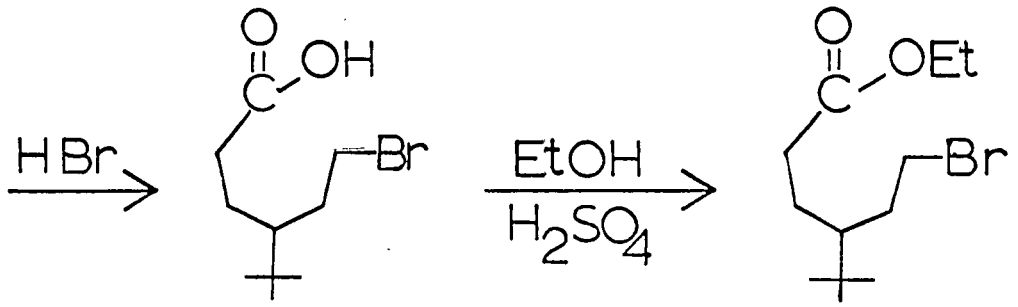
The treatment of cyclopentenone with t-butyl lithium or t-butyl magnesium chloride resulted in a 25% yield of isolable product. This material gave an infrared spectrum which indicated a mixture of unreacted

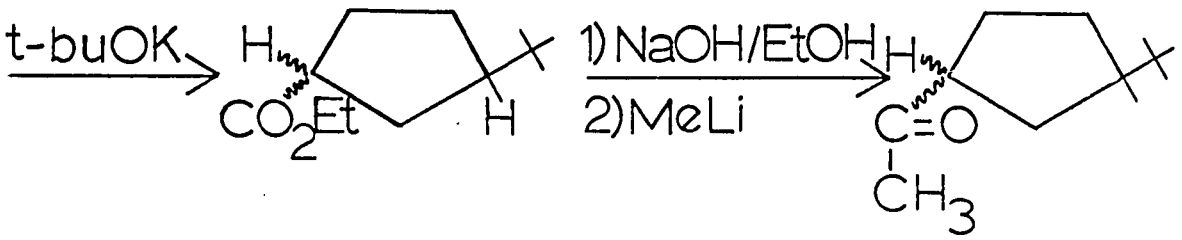
starting material, a cyclopentanone, and an alcohol. Polymeric material is the main product of the reaction, with both 1,2 and 1,4 addition of the t-butyl anion being indicated from the infrared spectrum. The structure of the 3-t-butylcyclopentanol (from hydroboration of 3-t-butylcyclopentene) was proven by its independent synthesis shown in Figure 1. Although the yield of each individual step is high (greater than 85%), the overall yield and the number of steps involved make this synthesis impractical for the preparation of large amounts of the 3-substituted alcohol. Nuclear magnetic resonance (NMR) indicates the ratio of cis- to trans-alcohol is approximately 55:45 (vide infra). This is probably the equilibrium mixture of the cis- and trans-3-t-butylcarbethoxycyclopentanes formed during the ring closure of ethyl 4-t-butyl-6-bromohexanoate using potassium t-butoxide or formed during the subsequent ethanolic sodium hydroxide saponification of the ester.

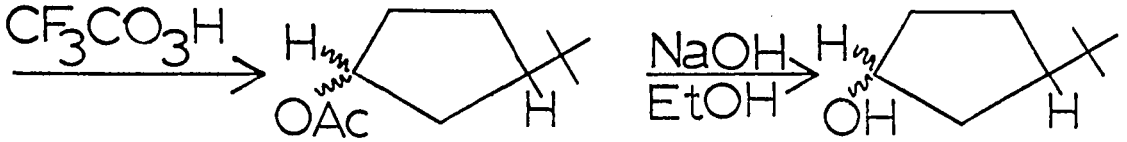
In an effort to prepare the cis-alcohols, the 2- and 3-t-butylcyclopentanones (prepared by oxidation of the respective alcohols with chromic acid in acetone) were reduced using lithium aluminum hydride in ether. It has been noted (100) that ketones which are only slightly sterically hindered yield the most stable alcohol (product development control) upon reduction with a metal hydride; whereas with ketones that are sterically hindered or with bulkier reducing agents, such as lithium-tri-t-butoxyaluminum hydride, the approach of the reducing agent is from the less sterically hindered side to give a predominance of the less stable alcohol (steric approach control). The 3-t-butylcyclopentanone gave a mixture of 55% cis- and 45% trans-3-t-butylcyclopentanol---analyzed by gas phase

Figure 2. Synthesis of 3-t-butylcyclopentanol.


OH
$Na_2Cr_2O_7$
CF_3CO_3H
O
O

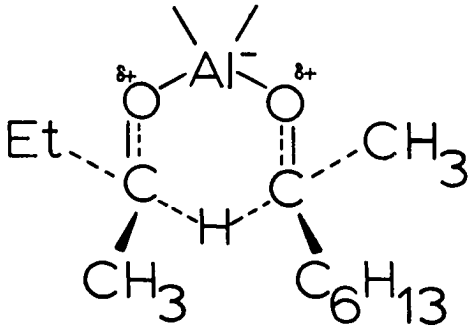

HBr
OH
Br
EtOH
H_2SO_4
OEt
Br


t-buOK
CO_2Et
H
1) NaOH/EtOH
2) MeLi
C=O
CH_3


CF_3CO_3H
OAc
H
NaOH
EtOH
OH
H

chromatography (GPC) using a 100 meter Golay capillary column with a Silicon SE 30 liquid phase. This is approximately the same ratio that was observed in the reduction of 3-iso-propylcyclopentanone (26) to give 55-61% of the cis-3-alcohol. Reduction of 2-t-butylcyclopentanone with lithium aluminum hydride in ether gave a 50:50 mixture of cis- and trans-2-t-butylcyclopentanols. Smat (89) found that reduction of 2-phenylcyclopentanone with lithium aluminum hydride gave 59% trans- and 41% cis-2-phenylcyclopentanol.

Equilibrations of the 2- and 3-t-butylcyclopentanols were carried out under Meerwein-Ponndorf-Verley-Oppenauer (MPVO) conditions. The generally accepted mechanism for this reaction involves 1.) coordination of the ketone to the aluminum alkoxide monomer, 2.) transfer of hydride from alkoxide to the ketone, 3.) separation of the ketone produced from the alkoxide, and 4.) alcoholysis of the mixed alkoxide. Step 2 of the above mechanism, involving the transfer of hydride ion, has been generally considered to be rate determining (101) although Shiner and Whittaker concluded that the rate-determining step is alcoholysis of the mixed alkoxide from their observation that the rate of α-phenylethanol formation is considerably slower than the rate of acetone formation in the reduction of acetophenone with aluminum isopropoxide (102). A rho value of 1.3 has been measured for the reaction of substituted benzophenones with diethylcarbinol and an optically active reductant has been shown to give a partially active product (asymmetric synthesis). These and other results are consistent with a cyclic transition state 11 for the transfer of hydride (10). The order of the MPVO reduction of benzophenone by



(11)

aluminum isopropoxide has been measured as first order in benzophenone and approximately 1.5 order in aluminum isopropoxide. To account for this, two simultaneous mechanisms are proposed---the above-mentioned cyclic transition state and one which involves a noncyclic transition state and 2 moles of aluminum isopropoxide (103). Shiner and coworkers have shown that aluminum isopropoxide is tetrameric in a number of organic solvents and at higher temperatures it is converted into a cyclic trimer (104). If these were the reacting species in addition to dissociated monomer, one would expect a higher reaction order for the aluminum alkoxide. Recent studies by Yager and Hancock (101) on the reduction of a number of methyl ketones with 9-fluorenol and aluminum t-butoxide indicate the kinetic order is 1 for acetone, 9-fluorenol and aluminum t-butoxide, and both the reaction between 9-fluorenol and aluminum t-butoxide and the hydride ion transfer are slow steps in the overall reaction. They also observed steric effects were important in the MPVO reaction as di-t-butyl ketone couldn't be reduced and di-t-butylcarbinol couldn't be oxidized under the reaction conditions.

Equilibration of an 55:45 mixture of cis- to trans-3-t-butylcyclopentanol for 9 days gave a mixture containing 52% of the cis-alcohol and

48% of the trans-alcohol. Since the resolution of isomers was incomplete using a 100 meter Golay column (column deteriorated after 1 months use) the isomer ratios for the 3-t-butylcyclopentanols are approximate values. Temin and Baum observed a 50:50 mixture of cis- and trans-isomers when cyclopentane-1,3-dicarboxylic acid was equilibrated with hydrochloric acid (105). Hückel and Bross (26) observed reduction of 3-iso-propylcyclopentanone with aluminum isopropoxide produced 82% of the cis-3-alcohol. The activity of the aluminum isopropoxide (sublimed) was measured by reducing cyclohexanone and the equilibration procedure was checked using a mixture of the two diastereoisomeric trans-2-decalols. Whereas cyclohexanone is reduced with aluminum isopropoxide to greater than 99% cyclohexanol after 24 hours, 2-t-butylcyclopentanone was converted to only 52% of the cis- and trans-2-alcohols after reaction for one week. GPC on a 4 ft. LAC 446 column indicated the ratio of cis-2-t-butylcyclopentanol to trans-2-t-butylcyclopentanol was 90:10. Steric effects are, thus, involved in the coordination of 2-t-butylcyclopentanone to the aluminum alkoxide and hydride transfer occurs almost exclusively from the less hindered trans- side to give the cis-2-alcohol. In the case of the 2-methylcyclopentanone, reduction is much faster using aluminum isopropoxide with not as great an apparent preference for the formation of cis-2-alcohol. Hückel (25) determined 58% cis-2-methylcyclopentanol was formed after 7 hours with 53.5% cis-2-methylcyclopentanol being formed after 18 hours.

The equilibration of a 50:50 mixture of cis- and trans-2-t-butylcyclopentanol using commercial aluminum isopropoxide for a period of 8

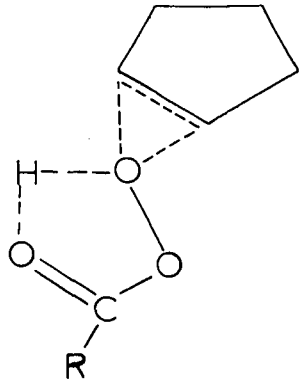
months yielded a 53:47 mixture of trans- to cis-2-t-butylcyclopentanol. Smat (89) observed a 63:37 ratio of trans-2-phenylcyclopentanol to cis-2-phenylcyclopentanol after equilibration of an initial 59% trans- and 41% cis mixture of the alcohols with aluminum isopropoxide. However, Dauben and coworkers (106) have observed that trans-2-methylcyclohexanol predominates in the equilibrium mixture to the extent of 99% in the cyclohexane series. Equilibration of pure trans-2-t-butylcyclopentanol for 11 days using sublimed aluminum isopropoxide gave no cis-2-alcohol and less than 1% of 2-t-butylcyclopentanone, whereas cis-2-t-butylcyclopentanol under the same conditions gave 40% of 2-t-butylcyclopentanone and a 78:22 mixture of cis- to trans-2-t-butylcyclopentanol. Formation of the aluminum alkoxide prior to oxidation should be much more rapid with the trans-2-alcohol than with the cis-alcohol due to the bulk of the adjacent t-butyl group. The more rapid oxidation of the cis-2-t-butylcyclopentanol and the fact that 2-t-butylcyclopentanone is reduced to give primarily the cis-2-alcohol indicate that transfer of hydride ion is the rate determining step in this system. Apparently a cyclic transition state is less hindered when the hydride ion (to be received or transferred) is trans- to the adjacent t-butyl group in 2-t-butylcyclopentanol. The formation of the alkoxide (and alcoholysis) is more rapid and less sterically demanding than the hydride transfer step of the reaction.

As separation of the cis- and trans-alcohols proved difficult, other methods were attempted to prepare the pure isomers. A mixture of cis- and trans-3-t-butylcyclopentene oxides (formed from the epoxidation of 3-t-butylcyclopentene) was found to be separable on either a Nester/Faust

spinning band column or a 4 foot glass helices packed Todd column. Reduction of the pure cis- or trans-epoxide with lithium aluminum hydride and Raney nickel was found to give the four isomeric cis- and trans-2 and 3-t-butylcyclopentanols (Figure 3). The mixtures of 2- and 3-alcohols could readily be separated on a spinning band column.

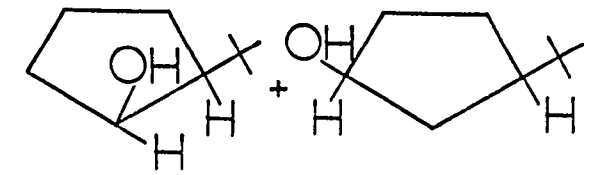
The preparation of the cis-3-t-butylcyclopentene oxide was attempted by formation of the bromohydrin and subsequent ring closure with base to the epoxide. It was thought that the initial bromination of 3-t-butylcyclopentene would be trans to the t-butyl group and subsequent attack of water should produce predominantly bromohydrin which would ring close to give the cis-epoxide. Two methods of bromohydrin formation were attempted using bromine water and potassium bromide (107) and N-bromosuccinimide in water (108). This was followed by treatment with either 15% sodium hydroxide or 0.1 M. t-butoxide/t-butyl alcohol. In all cases a dark brown oil was isolated, which was shown by IR and GPC to contain no epoxide.

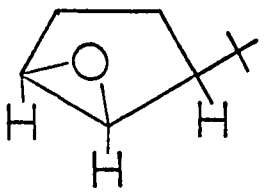
A variety of organic peracids and solvents were used in an attempt to increase the amount of cis-epoxide. The results of these studies are shown in Table 5. The generally accepted transition state for epoxidation is a spirano structure 12 involving the peracid and the olefin (109).



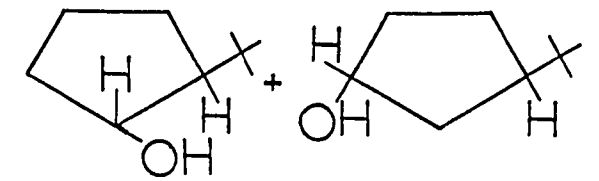
(12)

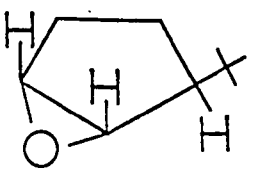
Figure 3. Synthesis of cis- and trans-2 and 3-t-butylcyclopentanols.





$LiAlH_4/Et_2O$	82%	18%
$Ni(Raney)/H_2$	12%	88%





$LiAlH_4/Et_2O$	100%	0%
$Ni(Raney)/H_2$	19%	81%

Table 5. Epoxidation of 3-t-butylcyclopentene as a function of organic peracid and solvent.

Peracid	Solvent	trans-Epoxide	cis-Epoxide
m-Chloroperbenzoic	Et_2O	78	22
m-Chloroperbenzoic	C_6H_{12}[a]	82	18
m-Chloroperbenzoic	EtOH[a]	90	10
Monoperoxyphthalic	Et_2O	78	22
Trifluoroperacetic	CH_2Cl_2	83	17
Peracetic	CH_2Cl_2	83	17
Peracetic	Et_2O	79	21

[a]Reaction was not quantitative.

Table 6. Epoxidation of substituted cyclopentenes in ether as a function of organic peracid.

Compound	Peracid	trans-Epoxide	cis-Epoxide
3-Isopropylcyclopentene	m-Chloroperbenzoic	42	58
3-Phenylcyclopentene[a]	m-Chloroperbenzoic	50	50
3-Phenylcyclopentene	Monoperoxyphthalic	48	52

[a]Dr. G. F. Morris, Dept. of Chemistry, Iowa State University, Ames, Iowa. Epoxidation of 3-phenylcyclopentene. Private Communication. 1965.

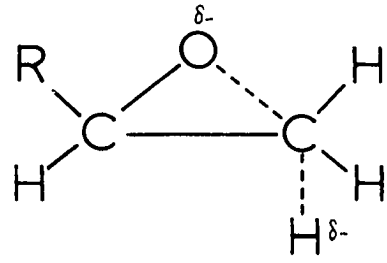
Henbest has shown that epoxidation of the symmetrical 4-methylcyclopentene with peroxylauric acid is insensitive to solvent effects. The ratio of trans-4-methylcyclopentene oxide to cis-4-methylcyclopentene oxide is 76:24, which is about the same ratio of trans/cis addition found in the hydroboration of this olefin (110). This suggests a steric effect of the methyl group in directing the epoxidation (3:1) to the trans-position. In the epoxidation of 3-t-butylcyclopentene a comparable steric effect was found in the formation of a 78:22 ratio of trans-epoxide to cis-epoxide. On the basis of Henbest's results for the epoxidation of 4-methylcyclopentene, one should expect a much greater percentage of trans-epoxide (approaching 100%) in the case of 3-t-butylcyclopentene because of the much greater bulk of the t-butyl group and the closer proximity (being in the 3-position) to the site of reaction. The fact that these two ratios are approximately the same may indicate that the cyclopentene ring is not planar and that puckering occurs in the 4-position. Puckering in the 4-position of 4-methylcyclopentene shields the olefinic bond (relative to the planar molecule) from cis-epoxidation, whereas puckering in the 4-position of 3-t-butylcyclopentene deshields the olefinic bond (relative to the planar molecule) from a cis- attack of peracid. It can be seen from Table 5 that the identity of the peracid has very little effect on the trans/cis-epoxide ratio and that solvent has a slight effect in the epoxidation of 3-t-butylcyclopentene. The fact that trans-epoxide is favored in a more polar solvent may be a result of the greater effective bulk of the epoxidizing agent. 3-Phenylcyclopentene gives a 50:50 mixture of cis- and trans-epoxides when treated with m-chloroperbenzoic

acid (Table 6). This ratio indicates either there are no steric factors present to direct the epoxidation toward the trans- position or there are concurrent polar or electronic effects of the phenyl group directing epoxidation toward the cis- position. The results of the epoxidation of 3-isopropylcyclopentene to give 58% cis- and 42% trans-3-isopropylcyclopentene oxide cannot be explained. Since there should be no polar or electronic factors associated with an isopropyl group to direct the peracid in a cis- manner, one would expect at most a 50:50 mixture of cis- to trans-epoxide with steric interference increasing the amount of trans-epoxide.

The isomeric 3-epoxides can be distinguished in the infrared. The cis-3-t-butylcyclopentene oxide absorbs at 11.63 μ whereas the trans-isomer absorbs at 11.94 μ. This epoxide doublet was also noted for isomeric mixtures of the 3-isopropylcyclopentene oxides and the 3-phenylcyclopentene oxides with the band for the trans-isomer occurring in each case at longer wavelength than the corresponding cis-isomer. The NMR spectra of the isomeric 3-t-butylcyclopentene oxides were also distinctive. The t-butyl group is deshielded by the oxygen in the cis-epoxide by 4.2 cps (cycles per second) and the hydrogen geminal to the t-butyl group is upfield in the cis-epoxide, whereas in the trans-isomer this proton cannot be distinguished from the other methylene protons. The oxirane protons in the cis-epoxide are found at higher field (3.21 ppm) than in the trans-isomer (3.29 ppm). It was also noted that the peak width at one-half peak heighth was 2.1 cps for the cis-epoxide hydrogens and 3.6 cps for the trans-epoxide hydrogens. This is probably due to a smaller difference in

chemical shift between the two epoxide protons and the smaller coupling constants in the case of the cis-isomer. The mass spectra of the cis- and trans-3-t-butylcyclopentene oxides were identical, except the intensities of peaks at 107 and 67 mass/electron units are slightly increased in the cis-epoxide. Characteristic of these spectra were a very small parent ion peak---140---a base peak---83---corresponding to loss of a t-butyl group, and a metastable ion at 37.4 corresponding to loss of carbon monoxide from base peak---83 to 55.

The stereochemistry and orientation of epoxide ring opening has been shown to involve a trans- attack of the nucleophile at the carbon atom bearing the greater number of hydrogens. This is generally the exclusive product of the reaction and steric effects are believed to promote this "normal addition" (111). It has been shown a.) that reagents avoid at-



(13)

tacking a carbon atom carrying an electron-withdrawing group even when attack at the alternative carbon atom must be subject to considerable steric hindrance and b.) that conjugating groups which can stabilize a positive charge by conjugation with a π orbital or an atomic p orbital favor attack on the adjacent carbon atom (111). These results indicate an S_N2 transition state where bond breaking is more important than bond making.

Although much work has been done on the steric effects of substituents attached to the epoxide-carbon atoms in reactions involving ring opening of epoxides (111), little work has been done on the steric effects of groups not directly attached to the reaction center. In the reduction of trans-3-t-butylcyclopentene oxide with lithium aluminum hydride in ether no 3-alcohol was formed. The bulky t-butyl group completely shields the cis-2-carbon atom from attack by the hydride ion. Reduction of cis-3-t-butylcyclopentene oxide gives 82% of the cis-2-alcohol and 18% of the cis-3-alcohol, indicating steric factors are also involved in shielding the trans-2-position from attack by the hydride ion. Dr. G. F. Morris has determined the lithium aluminum hydride reduction of the cis- and trans-3-phenylcyclopentene oxides gives the same ratio of 2- to 3-alcohol as was found in the t-butyl system. GPC of the reaction products and IR of the partially reduced epoxide indicate the absence of any carbonyl compound and the stereospecific trans- addition of hydride ion.

The kinetic reduction and product ratio of a mixture of cis- and trans-3-t-butylcyclopentene oxides with lithium aluminum hydride was studied as a function of solvent (Table 7). Small changes in the solvent mixture seem to have little effect upon the relative rates of epoxidation and the resulting alcoholic products, although further studies on solvent change would have to be made to substantiate these results. The unexpected small difference in rate of reduction of the cis- and trans-epoxides (a factor of 1.1 after correction for the rate of 3-alcohol formation in the cis-epoxide) indicates there is little steric interference in the 3-position, whether cis or trans, to attack by the hydride ion. It

Table 7. Kinetic reduction of a mixture of cis- and trans-3-t-butylcyclopentene oxides[a] with lithium aluminum hydride.

Solvent	Per cent reduction	Per cent epoxide remaining cis	Per cent epoxide remaining trans	Rate[b] cis/trans	Per cent 2-OH	Per cent 3-OH
100% Et_2O	88	20	80	1.34	89	11
50% Et_2O/hexane	91	19	81	1.31	91	9
100% Hexane[c]	71	37	63	.87	86	14

[a]Starting mixture contained 67.4% trans-epoxide and 32.6% cis-epoxide.

[b]Calculations using Weissberger's equation (vide infra).

[c]3 mls. of lithium aluminum hydride solution (1.1 M.) in ether added to 50 mls. of solvent, reaction mixture was slightly heterogeneous.

should be pointed out that this cis- to trans-epoxide rate ratio may be slightly low as the reductions were measured from 70-90% to completion. Reductions should either be run on an equimolar starting mixture of epoxides or should be measured after 15-20% reduction of the epoxides. Attack at the 3- position is favored in the cis-epoxide over attack at the 2- position by a factor of 4.6. The results in hexane are somewhat dubious as the system was heterogeneous. The apparent rate ratio in hexane may be a reflection of the relative solubilities of the epoxide.

Although the reduction of epoxides using hydrogen and a catalyst (Raney nickel or platinum oxide) has been known for some time (112) little use of this reaction has been made for synthetic purposes. A number

of unsymmetrical epoxides have been studied and in each case reduction occurs to give the least substituted alcohol (abnormal addition) (111). Thus, the alcoholic product can be changed by varying the reducing agent ---lithium aluminum hydride gives the most substituted alcohol, whereas Raney nickel gives the least substituted alcohol. A study of the platinum oxide catalyzed hydrogenation of substituted styrene oxides indicated that electron-withdrawing groups increased the percentage α-alcohol formed (styrene oxide and the p-methyl epoxide gave 100% of the β-alcohol) (113). The fact that the Hammett rho value for this reaction is negative and that there is a considerable substituent effect militates against a mechanism which involves simultaneous addition of hydrogen to the carbon and oxygen atoms. Bond breaking seems to be important in the transition state with some positive charge buildup on the α-carbon atom. The reduction takes place on the catalyst surface with the addition of either a proton or a hydrogen atom to the epoxide-oxygen, followed by the addition of a hydride ion or a hydrogen atom to the carbon atom.

Very little study has been directed toward the mechanism and stereochemistry of the hydrogenation of epoxides. Reduction of cis-3-t-butylcyclopentene oxide with Raney nickel and hydrogen yielded 88% of cis-3-t-butylcyclopentanol and 12% of the cis-2-alcohol, whereas reduction of trans-3-t-butylcyclopentene oxide produced 81% of the trans-3-alcohol and 19% of the trans-2-alcohol. Dr. G. F. Morris found in the reduction of the 3-phenylcyclopentene oxides the cis-isomer gave 100% of the cis-3-phenylcyclopentanol, whereas the trans-epoxide gives 36% of the trans-3-phenylcyclopentanol and 64% of the trans-2-isomer. The rate of reduction

of cis-3-phenylcyclopentene oxide was found to be 7 times the rate of the trans-isomer, whereas in the case of the 3-t-butylcyclopentene oxides, the trans-epoxide was reduced at a more rapid rate than the cis-isomer. NMR, GPC and IR indicated no carbonyl compound was present and the reaction was stereospecific, as the cis- and trans-epoxides upon reduction gave only the respective cis- or trans-alcohols.

The slower reaction rate of the cis-3-t-butylcyclopentene oxide can be explained by steric interference of the t-butyl group to coordination of the oxygen to the nickel surface. In the case of the cis-3-phenylcyclopentene oxide, this isomer may react faster due to coordination or adsorption of the phenyl group through its π-electrons to the catalytic surface which could either facilitate coordination with the cis-oxygen atom or stabilize the coordination to oxygen until reaction has taken place. The large ratio of 3-alcohol to 2-alcohol in the reduction of 3-t-butylcyclopentene oxide indicates a large amount of bond breaking in the transition state (product development control). The bulk of the catalyst and a moderate degree of puckering of the cyclopentane ring should result in a small difference in the 3- to 2-alcohol ratio for the reduction of the cis- and trans-epoxides. This was observed in the t-butyl system, but the predominance of the 2-alcohol (64%) in the reduction of trans-3-phenylcyclopentene oxide suggests little steric interference is involved in this system and the phenyl group is in some way directing epoxide ring opening toward the 2-position. The fact that the cis-phenyl epoxide gave only 3-alcohol, whereas the cis-t-butyl epoxide gave 88% 3-alcohol cannot be rationalized since the more bulky group should direct epoxide ring

opening toward the 3-position. If the bulky t-butyl group causes a large amount of puckering to occur and the phenyl group produces little or no puckering in the cyclopentene oxide, one could account for the difference in the alcoholic products. A great amount of work remains to be done on the mechanism of these catalytic hydrogenations and also the steric and electronic effects of different groups on the product ratios in these reactions. Neither the actual reducing hydrogen species nor its mode of addition to the epoxide bond is known.

A number of methods were attempted for the separation and identification of the cis- and trans-2 and 3-t-butylcyclopentanols prior to their preparation from the epoxides (vide supra). The liquid phase GPC column packings used for the attempted separation of the cis- and trans-isomers were UCON LB 550X, LAC 446, Silicone SE-30, Carbowax 1500, TCEP, THEED, Apiezon L and Zonel E-7. The cis- and trans-2-alcohols (and their corresponding acetates) were found to be separable only on a 4 ft. LAC 446 (1:5) on 60/80 mesh Chromosorb W column at 130°. No conditions were found where the cis- and trans-3-t-butylcyclopentanols could be separated by GPC, except for the short time that incomplete separation was obtained on a 100 meter Golay capillary column. A mixture of the acetates and silyl ethers synthesized from the 3-t-butylcyclopentanols could not be separated by GPC or differentiated from their NMR or IR spectra.

The NMR spectrum of a 60:40 mixture of trans- to cis-2-phenylcyclopentanol in deuteriochloroform and dimethyl sulfoxide contained two hydroxyl doublets at 4.47 (trans -OH) and 3.52 ppm (cis -OH). It is known that in dimethyl sulfoxide strong hydrogen bonding to the solvent shifts the hydroxyl resonance downfield (4.0 ppm) and reduces the rate of proton

exchange sufficiently to permit observation of the hydroxyl proton splitting (114). An NMR spectrum of a mixture of cis- and trans-3-t-butylcyclopentanol was obtained in dimethyl sulfoxide. The hydroxyl peaks weren't separated in this case and the splitting couldn't be observed as the peak fell under the downfield proton geminal to the hydroxyl group (4.18 ppm). Variation of the alcohol concentration or the addition of a small amount of nitrobenzene failed to shift the position of the hydroxyl proton substantially.

Dr. Lillien* has recently prepared a mixture of the 3-t-butylcyclopentanols by reduction of 3-t-butylcyclopentanone (prepared by the iron powder pyrolysis of 3-t-butyladipic acid). He, also, has not had any success in utilizing GPC for the separation of these compounds. Dr. Lillien separated the isomers by fractional crystallization of the p-nitrobenzoate esters from ethanol/water and he assigned the cis-configuration to the isomer melting at 64-65° and the trans-configuration to the ester melting at 41-42°. In the present investigation, reduction of the trans-3-t-butylcyclopentene oxide produced an alcohol which upon treatment with p-nitrobenzoyl chloride gave a derivative which melted 64-65° and the p-nitrobenzoate formed from the alcohol obtained by reduction of the cis-epoxide melted around 40°. The previous structure assignment by Lillien based on the melting points was, thus, shown to be incorrect.

---

*Dr. I. Lillien, Dept. of Chemistry, University of Miami, Coral Gables, Florida. Synthesis of 3-t-butylcyclopentanols. Private communication. (1965).

Although NMR cannot distinguish between mixtures of the cis- and trans-3-t-butylcyclopentyl derivatives, the spectra of the pure isomers are quite distinctive. Table 8 gives the chemical shifts and peak widths at one half peak height for a number of cyclopentyl derivatives. The methylene region (containing 7 protons) is rather sharp in the spectra of the cis-3-t-butylcyclopentanol, whereas this region is smeared out in the spectra of the trans-alcohol. This is probably due to the smaller difference in the chemical shifts of the protons in the cis-compound. These same characteristics were also noted in the NMR spectra of the cis- and trans-3-phenylcyclopentanols. It was thought that this difference in the methylene region between the cis- and trans-3-alcohols may also be due to a conformational effect. In cis-3-t-butylcyclopentanol the conformation may be held in an envelope conformation, analogous to that found for cis-1,3-dimethylcyclopentane, with puckering at the 2-carbon allowing the t-butyl and hydroxyl groups to occupy equatorial positions. Eclipsing in the trans-3-t-butylcyclopentanol could be minimized equally as well by puckering at the 2- or 3- carbon atoms. This would cause an averaging of the chemical shifts in the different conformations and would tend to spread out the methylene proton region. The NMR of these compounds was measured at low temperatures (-30 to -45°) in carbon disulfide. Although the peaks slightly broadened and the hydroxylic proton was shifted approximately 2 ppm downfield at -30°, there was no change in the patterns of the peaks in cis-3-t-butylcyclopentanol. However, on cooling trans-3-t-butylcyclopentanol to -40° the methylene peak sharpened by approximately 5 cps at half peak height and appeared to approach the pattern given by the cis-isomer. Further cooling (not attainable on the Varian A-60)

Table 8. Chemical shift and peak width at one half peak height for substituted cyclopentyl derivatives.

Compound	Methylene region		Downfield proton		t-Butyl
		Peak width[a]		Peak width[a]	
trans-3-t-Butylcyclopentanol	1.57	17.1	4.19	9.57	0.86
cis-3-t-Butylcyclopentanol	1.55	6.98	4.13	13.1	0.87
cis- And trans-3-alcohol[b]	1.57	8.12	4.15	14.0	0.87
trans-3-t-Butylcyclopentyl acetate	1.68	14.7	5.05	11.1	0.88
cis-3-t-Butylcyclopentyl acetate	1.64	10.4	4.99	12.4	0.91
trans-3-t-Butylcyclopentyl tosylate	1.76	15.2	4.84	11.8	0.82
cis-3-t-Butylcyclopentyl tosylate	1.64	14.8	4.79	11.8	0.84
trans-3-t-Butylcyclopentyl p-NO_2 benzoate	1.83	12.7	5.35	8.9	0.91
cis-3-t-Butylcyclopentyl p-NO_2 benzoate	---	----	5.32	13.0	---
3-t-Butylcyclopentyl bromide	2.04	16.7	4.19	19.1	0.90
trans-2-t-Butylcyclopentanol	1.57	9.48	3.94	6.81	0.89
cis-2-t-Butylcyclopentanol	1.63	10.2	4.23	6.29	1.01
trans-2-t-Butylcyclopentyl acetate	1.61	7.72	4.98	7.24	0.89
cis-2-t-Butylcyclopentyl acetate	1.70	6.90	5.19	6.55	0.98
trans-2-t-Butylcyclopentyl tosylate	1.67	20.1	4.69	8.58	0.81
cis-2-t-Butylcyclopentyl tosylate	1.67	7.49	5.03	5.10	0.91
Cyclopentyl acetate	---	----	5.08	10.0	---
trans-2-Phenylcyclopentanol	2.70[c]	12.4	3.93	10.0	---
cis-2-Phenylcyclopentanol	2.80[c]	16.3	3.98	5.9	
trans-2-Phenylcyclopentyl bromide	3.26[c]	11.1	4.04	16.1	
cis-2-Phenylcyclopentyl bromide	3.02[c]	24.2	4.55	10.1	

[a]Measured at half peak height, values in cps (cycles per second).

[b]Synthetic mixture containing 54.7% of the cis-3-t-butylcyclopentanol.

[c]Benzylic protons.

might give the same methylene pattern for both cis- and trans-isomers. These results indicate that conformational equilibrium may account for the difference in the NMR spectra of the cis- and trans-isomers and at lower temperatures the trans-alcohol may be frozen in the conformation that predominates for the cis-alcohol at room temperature. Similar differences in the NMR spectra are also noted (Table 8) for other 2- and 3-disubstituted cyclopentanes, although in some cases the differences are small compared to that observed in the 3-t-butylcyclopentanols. The IR spectra of the cis- and trans-cyclopentyl isomers were found to be identical in most of the cases studied.

A comparison of the chemical shifts of protons in substituted cyclopentyl compounds may be helpful in determining conformational effects in the five-membered ring. Tables 9 to 10 give the chemical shifts for the proton geminal to the functional group in a number of substituted and unsubstituted cyclopentyl derivatives. Although there seems to be no obvious relationship between the various chemical shift data and possible conformational differences in these compounds, some conclusions can be drawn from the data. A substantial amount of deshielding is evident in both the cis- and trans-3-phenylcyclopentyl compounds relative to the corresponding t-butyl compounds with this difference in chemical shift being approximately constant throughout the derivatives studied. The fact that deshielding is only slightly greater (0.04 ppm, 2.4 cps) in the trans-3-phenylcyclopentyl derivatives relative to the cis-3-isomer indicates that this shielding is not a spatial field effect of the phenyl group as the trans-3-proton (in the cis-isomer) is not located in a position to be affected by the phenyl group. The 2.4 cps chemical shift difference

Table 9. Chemical shifts of the cis-1-proton in trans-3-substituted cyclopentyl compounds.

Functional group R	trans-3-Phenyl cyclopentyl δ	trans-3-t-Butyl cyclopentyl δ	Cyclopentyl δ
-OH	4.42	4.19	4.14
-OAc	5.25	5.05	5.08
-Br	4.49	4.19	4.36
-OTos	5.05	4.84	4.93
-Cl	--	--	4.34

Table 10. Chemical shifts of the trans-1-proton in cis-3-substituted cyclopentyl compounds.

Functional group R	cis-3-Phenyl cyclopentyl δ	cis-3-t-Butyl cyclopentyl δ	Cyclopentyl δ
-OH	4.32	4.13	4.14
-OAc	5.18	5.02	5.08
-OTos	--	4.79	4.93

between the cis- and trans-3-protons must be due to long range deshielding of the cis-proton by the phenyl group. Since the 3-position is far enough removed from the phenyl group, it would not be deshielded as a result of an inductive effect through the four sigma-bonds. The remaining deshielding difference (0.16-0.19 ppm) between the 3-phenyl and t-butyl

compounds may well be a result of conformational effects and not the direct result of the phenyl substituent.

The 1-proton in the trans-3-t-butylcyclopentyl derivatives has approximately the same chemical shift as the corresponding proton in the unsubstituted compounds except in the case of the bromide (Table 9). The bulk of the bromine may be sufficient to change the conformation of the trans-3-t-butylcyclopentyl bromide relative to the other isomers. For example in the acetate, puckering at the 2-carbon atom may be important even though this results in the acetoxy group occupying an axial position---thus increasing steric interactions with the hydrogen atoms. The more bulky bromide might prefer the conformation in which the 3-carbon atom is puckered with the t-butyl group occupying an equatorial position at the tip of the flap in the envelope conformation. The bromide in this form would occupy a bisectional position and eclipsing may not be as pronounced as that expected in the conformation containing an axial bromine atom. If the half-chair conformation were also important in some of these compounds (the 1-substituent occupying a quasiaxial position), the chemical shifts of the protons would be an average of all conformations involved and would thus be shifted relative to the cyclopentane derivatives in which these conformations are not prominent.

The chemical shift of the proton geminal to the functional group is also of interest in the 2-substituted cyclopentyl derivatives. The values of the chemical shifts of the 1-proton in 2-substituted cyclopentyl compounds are given below to compare with those values reported in Tables 9 and 10.

Functional group R	trans-2-Phenyl cyclopentyl δ	trans-2-t-Butyl cyclopentyl δ	cis-2-Phenyl cyclopentyl δ	cis-2-t-Butyl cyclopentyl δ
-OH	3.93	3.94	3.98	4.23
-OAc	5.05	4.98	5.34	5.19
-Br	4.15	--	4.52	--

In comparing the cis- and trans-2-phenylcyclopentyl compounds one notes that as the bulk of the functional group increases (-OH, -OAc to -Br), the difference in chemical shift between the cis- and trans-proton also increases. This is undoubtedly the result of additional puckering due to increased interactions between the phenyl and functional groups---particularly evident in the cis-isomer. The fact that the chemical shift of the cis-proton is practically the same in the trans-2-phenyl and t-butylcyclopentyl acetates and alcohols indicates either the phenyl group is not free to rotate and the hydrogen lies in a region of zero shielding or the shielding and deshielding of the phenyl group in the different conformations fortuitously cancel each other. Johnson and Bovey (115) have calculated the amount of shielding and deshielding in aromatic compounds as a function of the position of a hydrogen atom. They also observed that the diamagnetic (positive shielding) region in the phenyl group is more spacious than the paramagnetic region, thus accounting for the net shielding effect experienced by a solute in benzene. The fact that the trans-proton in the cis-2-phenylcyclopentanol is shielded relative to the t-butyl compound may be accounted for by a large degree of puckering in the cyclopentane ring. Finally, conformational effects are also evident as the cis-proton in trans-2-t-butylcyclopentanol (3.94 ppm) is shielded

relative to cyclopentanol (4.14 ppm), whereas the proton in the cis-isomer (4.23 ppm) is deshielded relative to the unsubstituted compound.

The t-butylcyclopentyl p-toluenesulfonates were found to be very unstable. Decomposition of the 3-t-butylcyclopentyl isomers occurred upon drying at 60° and 0.1 mm. vacuum after 3 hours. The trans-2-t-butylcyclopentyl p-toluenesulfonate decomposed after 4 hours at 25° and 0.1 mm., and the cis-isomer decomposes at room temperature and atmospheric pressure within 1 hour. These compounds could be kept indefinitely in a desiccator at -20°. The NMR spectra of the light brown decomposition product of cis-2-t-butylcyclopentyl p-toluenesulfonate (after treatment with potassium t-butoxide followed by extraction with sodium bicarbonate) indicated no olefin was present. No indication as to the identity of the decomposition product could be determined since a complex mixture of peaks was obtained from 0.60 to 2.50 ppm.

Previous attempts (32) to prepare 2-phenylcyclopentyl bromide were unsuccessful. Free radical hydrobromination of 1- and 3-phenylcyclopentene failed to produce any bromides. Treatment of 3-phenylcyclopentene in glacial acetic acid at 100° for 4 hours with anhydrous hydrogen bromide produced a mixture of bromides with the 3-isomer predominating. Bromination of 1-phenylcyclopentene followed by dehydrobromination resulted in none of the desired product.*

Wiley and coworkers (116) have reported that the reactivity of alcohols toward triphenylphosphine dibromide paralleled the general order of

---

*W. Thornton, Dept. of Chemistry, Iowa State University, Ames, Iowa. Attempted synthesis of 2-phenylcyclopentyl bromide. Private communication. 1965.

reactivity in S_N2 reactions and that rearrangements were absent even in the preparation of neopentyl bromide. Schaefer and Weinberg (117) have recently shown in the norbornanol system that the course of bromination involves a concerted displacement of triphenylphosphine oxide moiety by bromide ion to produce an alkyl bromide of opposite configuration from that of the starting alcohol. This method was attempted for the stereospecific synthesis of the cis- and trans-2-phenylcyclopentyl bromides. Treatment of trans-2-phenylcyclopentanol with triphenylphosphine dibromide in acetonitrile resulted in less than a 30% yield of the desired bromide with unreacted starting material and the phenylcyclopentenes being the major contaminants. The trans-/cis-bromide isomer ratio was 53/47 according to NMR. Since cis-2-phenylcyclopentyl bromide was shown to be relatively unstable, this could have been the major product with subsequent elimination under the reaction conditions. Dimethylformamide was used as the reaction solvent and most of the triphenylphosphine oxide was removed by taking the bromide up in pentane prior to distillation, but the yield of the bromide wasn't substantially increased. Removal of all the triphenylphosphine oxide prior to distillation or purification by elution chromatography rather than distillation should render the bromides accessible by this method. Preparation of the bromides was also attempted by bubbling hydrogen bromide through a pentane-ether solution of cis-2-phenylcyclopentanol at -50°, but only starting material was isolated after one hour. Low temperature addition of hydrogen bromide to 1-phenyl-substituted ethanol, propanol, and butanol has been shown to proceed with retention of configuration (118).

A mixture of cis- and trans-2-phenylcyclopentyl bromides was prepared by treating trans-2-phenylcyclopentanol with 48% hydrobromic acid and lithium bromide at 70° for 15 hours. NMR and GPC indicated the ratio of trans-bromide to cis-bromide was 74:26. The bromination of threo-1,2-diphenylpropanol with lithium bromide and hydrobromic acid produced the threo-bromide with 75% retention of configuration.* Upon treatment with lithium bromide and hydrobromic acid, cis-2-phenylcyclopentanol afforded a mixture of bromides in only 15% yield (after distillation). The ratio of trans- to cis-2-phenylcyclopentyl bromide was 75/25 as indicated from NMR. Since decomposition of the bromides, especially the cis-isomer, to olefins was noted on distillation, the above ratio may actually be lower with the possibility of the cis-isomer being predominant. The mechanism for this bromination reaction is not known. Further study on other systems is required to determine if the reaction giving 75% retention of configuration is general or fortuitous in the systems studied---possibly the result of a β-phenyl substituent.

3-t-Butylcyclopentyl bromide was prepared in 76% yield by treating trans-3-t-butylcyclopentanol with lithium bromide-hydrobromic acid at 67° for 12 hours. However, the attempted preparation of the 2-t-butylcyclopentyl bromides proved difficult. The reaction of lithium bromide and hydrobromic acid with trans-2-t-butylcyclopentanol for 19 hours at 52° followed by elution chromatography gave a mixture of two compounds. These same compounds were prepared from the similar reaction of cis-2-t-

---

*D. Best, Dept. of Chemistry, Iowa State University, Ames, Iowa. Preparation of bromides. Private communication. 1965.

butylcyclopentanol at 55° for 18 hours. One product appeared (NMR) to be 2-t-butylcyclopentyl bromide and the other was a rearranged bromide. The bromination of trans-2-t-butylcyclopentanol was repeated at a slightly higher temperature and after distillation the exclusive product was the rearranged bromide produced in greater than 50% yield.

NMR of the rearranged bromide indicated 3 methyl groups at 1.03, 1.15 and 1.75 ppm and no proton absorption below 2.0 ppm. A double resonance experiment (irradiating from 1.5 to 2.0 ppm) failed to collapse the two methyl peaks (separated by 8 cps) at 1.03 and 1.15 ppm. This indicates the absence of an isopropyl group and the presence of 3 different methyl groups. The deshielded methyl group (1.75 ppm) is attached to the carbon atom containing bromine and the infrared spectrum supports the presence of a gem-dimethyl group and a cyclohexane ring. This evidence indicated the compound to be 1,2,2-trimethylcyclohexyl bromide---attainable by a 1,2-hydride shift in the 2-t-butylcyclopentyl carbonium ion, followed by 1,2-methyl migration with subsequent ring expansion and addition of a bromide ion. The mass spectra of the compound further substantiates this structure. No parent ion peak was observed. The base peak at 109 mass/electron units corresponds to loss of a methyl group and hydrogen bromide. A metastable peak at 41.2 corresponds to loss of a 3 carbon fragment (109 to 67) from the base peak (dimethylcyclohexene cation). The other major peaks can be readily accounted for as follows: 124, loss of hydrogen bromide from the parent ion; 81, loss of ethylene in a retro-Diels-Alder reaction from the base peak; 57, loss of a saturated butyl fragment; and 55, loss of dimethylacetylene from the base peak leaving a 4 carbon fragment. It appears that 2-t-butylcyclopentyl

bromide is the kinetic reaction product and this rearranges upon heating or longer reaction time to give 1,2,2-trimethylcyclohexyl bromide.

Treatment of 1,2,2-trimethylcyclohexyl bromide and the mixture of two bromides obtained from cis-2-t-butylcyclopentanol with potassium t-butoxide/t-butyl alcohol for 3-4 days at 65-70° gave the same number of olefins, but in different percentages. GPC showed five olefinic compounds were formed from the eliminations with two of these being 1-t-butylcyclopentene and 3-t-butylcyclopentene. NMR indicated the presence of an exo-methylenecyclohexane to further substantiate the structures of the bromides.

The attempted preparation of the 2-phenylcyclohexyl bromides utilizing the same method employed for the synthesis of the corresponding cyclopentyl compounds was unsuccessful. Depending upon the reaction conditions, either starting material or olefin was formed. trans-2-Phenylcyclobutanol was also treated with lithium bromide and hydrobromic acid at 65° for 12 hours. NMR indicated the major product (approximately 50%) was the ring opened compound, 1-phenyl-4-bromobutene. Other products present were a cyclopropane compound, a cyclobutane compound (probably the desired 2-bromide with the proton geminal to the bromide occurring at 4.81 ppm), and possibly small amounts of 1-phenylcyclobutene and starting alcohol.

Elimination Reactions

The rates of elimination of unsubstituted cyclopentyl compounds were previously reported by Smith (32). This system contains a secondary alpha-carbon atom and the conformational problems associated with a five

membered ring, but does not have an activated beta-proton in contrast to the 2-phenylcyclopentyl p-toluenesulfonate system. These factors should shift the transition state for the elimination toward the "nearly E1" end of the E2 mechanistic spectrum. The unsubstituted cyclopentyl system can serve as a model in comparing the rates of elimination of the 2- and 3-phenyl- and t-butylcyclopentyl derivatives in order to get some indication of the effect of conformational changes on the dihedral angle and the rate of elimination. This system should also be of interest in determining the effect of an "E1 like" transition state on the bromide/p-toluenesulfonate rate ratio.

Although the reactivity of p-toluenesulfonates relative to halides is great in S_N1 reactions (relative rates of solvolysis in ethanol are Tos:I:Br = 20 : 2 : 1) (119), there appears to be a resistance of the p-toluenesulfonate group in undergoing beta-elimination and S_N2 reactions. Bumgardner (120) has recently observed that treatment of 3-phenylpropyl derivatives with sodium amide in liquid ammonia gives exclusively gamma-elimination in the case of the p-toluenesulfonate group to form phenylcyclopropane, whereas the bromide gives 100% beta-elimination to produce the olefin. Arnold and coworkers (121) have demonstrated that differences between primary alkyl bromides and p-toluenesulfonates become magnified in an environment which strongly favors elimination reactions. Thus, treatment of n-octadecyl bromide with potassium t-butoxide gave 85% elimination, while n-octadecyl p-toluenesulfonate under the same conditions gave at least 98% of the substitution product.

A comparison of the relative bromide/p-toluenesulfonate rate ratio for a variety of substrates is given in Table 11. The bromide was shown

Table 11. A comparison of the relative bromide to p-toluenesulfonate rate ratios for elimination in a number of systems.

System	Solvent[a]	Temp. (°C.)	$k_2 \times 10^4$ Br	$k_2 \times 10^4$ Tos	k_{Br}/k_{Tos}	% E2 Br	% E2 Tos	Ref.
$CH_3CH_2CH_2X$	EtOH	40	1.26[b]	4.58[b]		9	Small	(119)
$CH_3(CH_3)CHCH_2X$	EtOH	55	1.4	1.8	1.06[c]	60	44	(119)
n-$C_{18}H_{37}X$	t-BuOH	40	0.23	1.51	>13[c]	84	<01	(121)
$C_6H_5CH_2CH_2X$	EtOH	30			11[c]	96	33	(81)
	EtOH	50	34.2	5.98	5.72			
	t-BuOH	50	369.0	111.0	3.32	100	100	
$C_6H_5(CH_3)CHCH_2X$[d]	t-BuOH	50		2.16				
$C_6H_5CH_2(CH_3)CHX$	EtOH	50	19.2	3.42	5.61			(82)
	t-BuOH	50	94.1	9.32	10.1			
$C_6H_5CH_2(CH_3)_2CBr$	EtOH	50	19.2					(82)
	t-BuOH	50	2.37					
Cyclopentyl	t-BuOH	50	1.82	3.89	1/2.14			
cis-2-phenylcyclopentyl	EtOH	50		24.2				(32)
	t-BuOH	30	241.0	5.90	40.8			
	t-BuOH	50		29.1				
trans-2-phenylcyclopentyl	t-BuOH	30	0.039	0.47	1/12.1			(32)
	t-BuOH	50	0.285	2.9	1/10.2			
	t-BuOH	70	1.96	17.5	1/8.9			

[a]Base is the conjugate base of the solvent in all cases.

[b]Rate is the summation of the S_N2 and E2 processes.

[c]Ratio is corrected for S_N2 product formed.

[d]D. Storm, Dept. of Chemistry, University of Colorado, Boulder, Colorado. Elimination of 2-phenylpropyl p-toluenesulfonate. Private communication. 1966.

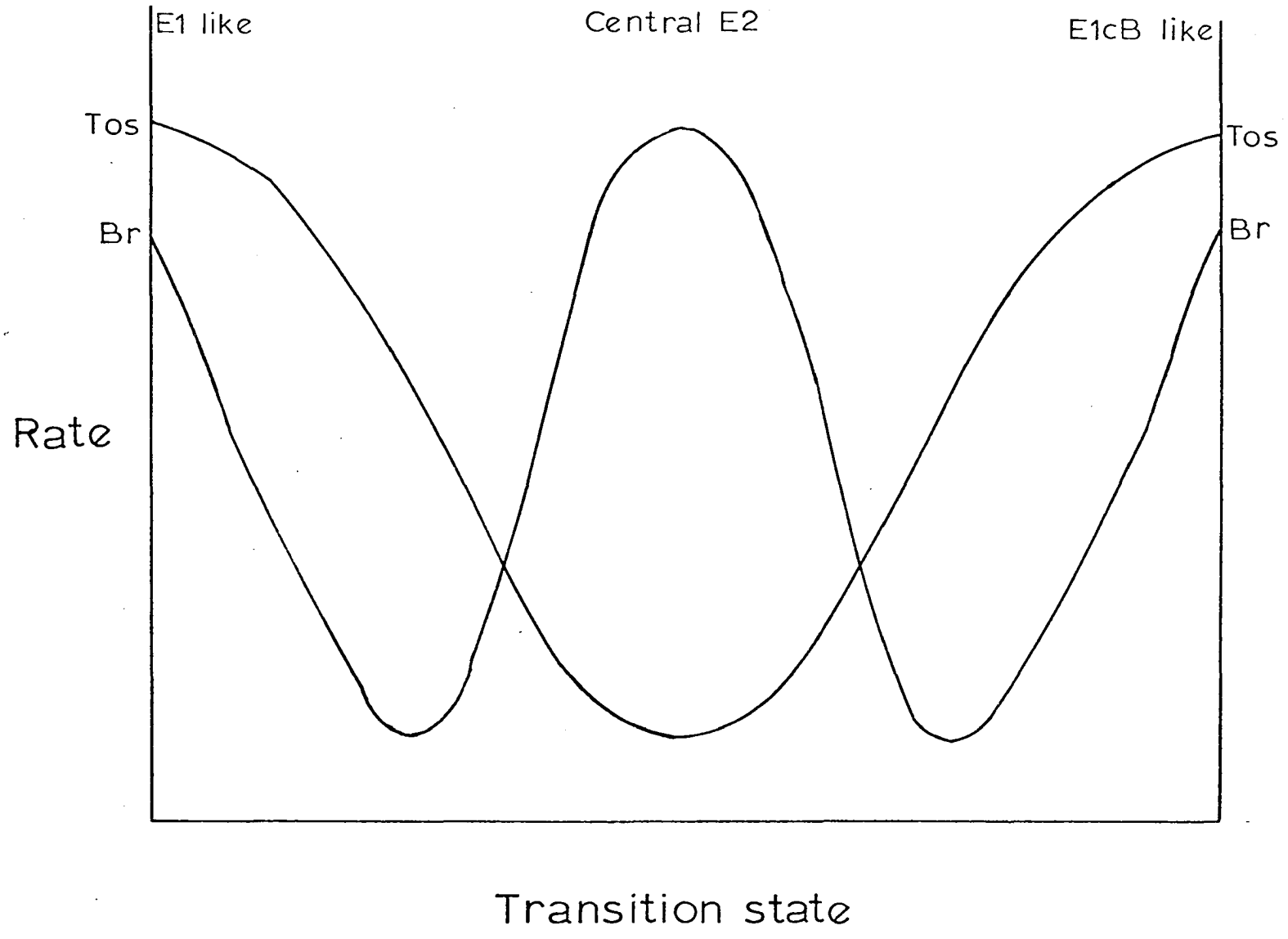
to react faster in most of the systems studied with the exception of cyclopentyl p-toluenesulfonate and trans-2-phenylcyclopentyl p-toluenesulfonate. Bishop (81) has suggested that the leaving group ability of the p-toluenesulfonate group is strongly dependent on the amount of carbon-oxygen bond breaking in the transition state. The p-toluenesulfonate group was proposed to be a poor leaving group when little carbon-oxygen bond breaking exists in the transition state. Conversely, when carbon-oxygen bond breaking is extensive, the effect of resonance stabilization of the partial negative charge could conceivably make p-toluenesulfonate a good leaving group. Bishop has also suggested that the bromide/p-toluenesulfonate rate ratio might be useful as a qualitative measure of the extent of alpha-carbon bond breaking to determine the position of an elimination in the E2 spectrum of transition states. The greater reaction rate of cyclopentyl p-toluenesulfonate (2.1 times the corresponding bromide) may be a result of the "E1 like" transition state, since the carbon-leaving group bond has been largely broken due to the secondary alpha-carbon atom and unactivated beta-protons in this system. In the trans-2-phenylcyclopentyl compounds (p-toluenesulfonate reacts approximately 10 times faster than the bromide) the cis-elimination is not as concerted as the trans-elimination would be in the corresponding cis-2-phenyl isomer. Therefore the transition state for the cis-elimination should lie further on the ElcB side, since in these systems the phenyl group can stabilize negative charge formation on the beta-carbon atom. In this case greater reactivity of the p-toluenesulfonate relative to the bromide may be explained by its ability to stabilize inductively the

beta-negative charge because of the greater electronegativity of the p-toluenesulfonate group.

The data reported thus far on the bromide/p-toluenesulfonate rate ratio is consistent with the supposition that, whenever possible, bromide eliminations are highly concerted, synchronous processes, whereas p-toluenesulfonate eliminations require driving force from extensive carbon-oxygen or carbon-hydrogen bond breaking. In the central E2 region where bond making and bond breaking are approximately equal the bromide will react faster than the p-toluenesulfonate, but as the reaction becomes less concerted the elimination rate of the p-toluenesulfonate increases relative to the bromide. On the E1 side the p-toluenesulfonate group facilitates carbon-oxygen bond breaking due to resonance stabilization and greater solvation of the leaving group, while on the E1cB side the p-toluenesulfonate may facilitate proton removal through the inductive stabilization of the anion on the beta-carbon atom.

The relative rate ratios of the different halogen derivatives were shown to be constant from the beta-phenylethyl and cyclopentyl systems (81, 32), whereas the relative rate of the p-toluenesulfonate group was dependent upon the system studied. The large difference observed in the bromide/p-toluenesulfonate rate ratio (Table 11) indicates the transition state of an elimination reaction is undoubtedly important in determining this ratio. A correlation of the transition state with the relative bromide and p-toluenesulfonate rates which fits the available data is shown in Figure 4. In the diagram the elimination rate of the p-toluenesulfonate for a given compound is shown to decrease toward a minimum as the

Figure 4. Correlation of the transition state with the relative rates of bromide and p-toluenesulfonate elimination.


E1 like
Central E2
E1cB like
Tos
Br
Tos
Br
Rate
Transition state

elimination becomes more concerted. In fact, eliminations which are forced into the central E2 region (primary carbonium ion and unactivated beta-hydrogen) may react by another pathway, e.g., substitution competes favorably in the primary alkyl derivatives (121) and gamma elimination is prevalent in the 3-phenylpropyl p-toluenesulfonates (120). It might not be possible for a p-toluenesulfonate to undergo a completely concerted elimination, but may always require some driving force from C-O or C-H bond breaking. Olefin product studies on the eliminations of the 2-substituted butyl and pentyl systems indicate that less double bond formation is present in that transition state for p-toluenesulfonate eliminations relative to the bromide eliminations (71, 79, 80). In fact Brown has recently shown (122) in the eliminations of 2-butyl and 3-pentyl p-toluenesulfonates with potassium t-butoxide/t-butyl alcohol that the cis-2-olefin predominates over the trans-2-olefin. Therefore, very little eclipsing of the adjacent groups must occur in the transition state of these compounds. Along with rho values and isotope effects, this further confirms the inability of the p-toluenesulfonate moiety to remove a buildup of negative charge on the beta-carbon atom. The lack of reactivity of the p-toluenesulfonate compounds in the central E2 region cannot be explained at the present time.

In Figure 4 the reactivity of the bromide is postulated to be maximum in the central E2 region for a given compound and to pass through minima in each "in between" region prior to reaching maximum values at the extreme E1 and E1cB sides in the E2 transition state spectrum. If one takes, for example, a bromide elimination occurring at the far E1cB extreme and shifts the transition state slightly toward a more concerted

reaction (introduce a beta-methyl group) the reaction rate should decrease, since the primary driving force for the ElcB reaction has also been decreased by this change in structure. Similarly, any change which shifts an elimination from the El extreme should also decrease the reaction rate. The bromide, in contrast to the p-toluenesulfonate, is able to efficiently remove charge buildup on the beta-carbon atom and react in a concerted manner---as was shown by product ratios, isotope effects and rho values (71, 81). This may be due to the high degree of polarizability of the C-Br bond. A difficulty encountered in these eliminations is that one does not know what the relative rates for a given compound would be as the transition state changed from El to concerted to ElcB. One might predict that "other things being equal" a completely concerted elimination would be the fastest, as bond making would assist bond breaking and removal of the beta-proton would facilitate carbon-leaving group bond breaking and vice versa. Any change in transition state from a completely concerted reaction should decrease the reaction rate for a given compound, thus, the largest reaction rate is pictured in the central E2 region. All available data on the relative bromide/p-toluenesulfonate rate ratio can be correlated by Figure 4, whether or not the transition state is similar for each of the leaving groups in a given compound.

The data at present cannot distinguish the above correlation from the possibility that the relative reactivity of bromide and p-toluenesulfonate arises from a different transition state of the two compounds. One might assume that the p-toluenesulfonate is always more reactive than the bromide for a given transition state, since it should be more reactive at both the El and ElcB extremes (vide supra). This difference in

rates need not be consistent throughout the spectrum of transition states, i.e., this rate difference might be small in the central E2 region because of apparent reactivity of bromide in a concerted reaction. The greater reactivity of bromide relative to the p-toluenesulfonate in some instances may be a result of a difference in transition states between the two compounds. The transition state may shift for the bromide elimination so that the bromide can take out part of the negative charge (become more "E1 like") which has developed on the beta-carbon atom in the transition state. Thus, the bromide can react at a faster rate than the p-toluenesulfonate, since the transition states for the two compounds are different. In compounds whose transition states lie at either extreme (E1 or E1cB) or whose bromide and p-toluenesulfonate transition states are the same for some reason (e.g., in cis-eliminations) the p-toluenesulfonate would be more reactive than the bromide.

It should be pointed out that the above correlations are based on the available kinetic data and may be useful only in presenting a new way of looking at the transition states of these elimination reactions and predicting the results of future experiments. Relative rate studies on additional systems coupled with Hammett rho correlations, isotope effects, and product ratio studies are required to test the generality of these conclusions and determine the correlation between the transition state and relative rate ratio which is applicable.

The reacting bond rule proposed by Swain and Thornton (123, 124) predicts that p-toluenesulfonate should react slower than bromide in the central E2 region as the transition state for the p-toluenesulfonate

looks more like reactants with less double bond formation. This rule, though, would also predict the same order of reactivity in the "E1 like" and "E1cB like" transition state regions. Changing from t-butyl alcohol to the more polar ethanol as solvent should increase the rate of bromide relative to p-toluenesulfonate since this bond is more subject to solvation as it is longer in the transition state and resembles products to a greater extent. This bromide rate enhancement is observed in the 2-phenylethyl system, but the trend is reversed in the 1-phenyl-2-propyl compounds as k_{Br}/k_{Tos} increases in going to t-butyl alcohol. The reacting bond rule may also prove useful in determining the effect of changing the base strength in an elimination reaction, although it cannot predict the amount of charge buildup on the alpha- and beta-carbon atoms.

Previous investigators have reported that different batches of potassium t-butoxide/t-butyl alcohol gave rate constants which were not always reproducible (33). The major source of difficulty was traced to impurities in the potassium metal. The potassium in this work was rigorously purified prior to use and the base solution was checked by determining the rate at which it induced elimination from 2-phenylethyl tosylate. The second order rate constant determined spectrophotometrically for 2-phenylethyl tosylate was $k_2 = 2.17 \times 10^{-3}$. This is slightly higher than the value (1.90×10^{-3}) determined by Smith (32). The two batches of base prepared gave rate constants for a number of compounds which were consistent and reproducible.

The increased elimination rate of cyclopentyl p-toluenesulfonate compared to the bromide might be the result of a competing unimolecular reaction with solvent (solvolysis), since p-toluenesulfonate is known to

react faster than the bromide under E1 and S_N1 conditions (vide supra). Analysis of the products by GPC and NMR at the infinity point of the eliminations using potassium t-butoxide indicated cyclopentene was the only product (no substitution product was observed). The quantitative bromination procedure of Siggia (125) was also used to determine the per cent cyclopentene formed in the elimination of cyclopentyl p-toluenesulfonate and cyclopentyl bromide. The bromide was shown to give 100% cyclopentene under these conditions, whereas the p-toluenesulfonate gave greater than 94% cyclopentene. Correction for the losses of the olefin during the elimination and bromination reactions due to its high volatility were made by processing a blank solution, containing a known amount of cyclopentene and an equimolar amount of p-toluenesulfonic acid, in an identical manner. These results indicate that solvolysis is not occurring in this system to give substitution products, but do not rule out the possibility of a simultaneous unimolecular reaction (E1) which gives cyclopentene as the sole product.

The E1 process was ruled out in this system by acidimetrically determining the rate constants at different base concentrations (Table 12). Increasing the base concentration should decrease the second order rate constant if a unimolecular reaction is simultaneously occurring (vide infra). One, in fact, observes an actual rate enhancement of 1.12 for the bromide and p-toluenesulfonate upon increasing the potassium t-butoxide concentration from 0.1 to 0.3 molar. This is undoubtedly the result of salt effects, since higher ionic strengths favor reactions which require charge separations in the transition state. Rate accelerations in the range of 1.08-1.57 have been reported by Smith (32) in changing from

Table 12. Rates of elimination of cyclopentyl p-toluenesulfonate and halides in potassium t-butoxide/t-butyl alcohol.

Cyclopentyl compound	Temp. (°C.)	Base conc. (moles/liter)	$k_2 \times 10^4$	Relative rate
I[a]	50	0.10	10.6	407
OTos	50	0.10	3.89	150
Br	50	0.10	1.82	70
Cl	50	0.10	0.026	1
OTos	50	0.30	4.36	
Br	50	0.29	2.03	
Br	70	0.11	12.1	

[a]Ref. (32).

0.1 to 0.3 M. base for the 2-arylcyclopentyl and 2-phenylethyl p-toluenesulfonate systems. The fact that k_{Tos}/k_{Br} remains constant (2.14) upon changing the base concentration also indicates that one is measuring only a second order elimination. Since an E1 reaction would be more important in the reaction of the p-toluenesulfonate relative to the bromide, this compound would be more sensitive to changes in base concentration and the k_{Tos}/k_{Br} rate ratio should decrease at higher base concentrations.

In contrast to cyclopentyl p-toluenesulfonate, it was immediately apparent that an E1 process was occurring in the elimination of the 2-t-butylcyclopentyl p-toluenesulfonates. The olefinic product ratio and the measured second order rate constant were dependent upon the initial base concentration (Table 13). If an unimolecular reaction were competing

Table 13. Kinetics and product analysis from the potassium t-butoxide/t-butyl alcohol elimination of 2-substituted cyclopentyl p-toluenesulfonates.

p-Toluenesulfonate	Temp. (°C.)	Base conc. (moles/liter)	$k_2 \times 10^4$	Per cent 1-olefin	Per cent 3-olefin
cis-2-t-Butylcyclopentyl	50	0.11	15.9	94	06
	50	0.27	6.86	85	15
	50	0.29	6.90	83	17
	50	1.38		35	65
	50	t-buOH[a]		100	00
	30	0.11	1.97		
trans-2-t-Butylcyclopentyl	50	0.11	1.16	65	35
	50	0.27	1.08	32	68
	50	0.29	1.02	30	70
	50	0.98		05	95
	50	1.38		02	98
	50	t-buOH[a]		95	05
	70	0.11	9.59		
cis-2-Phenylcyclopentyl[b]	50	0.10	29.10	100	00
trans-2-Phenylcyclopentyl[b]	50	0.10	3.1	91	09
cis-2-Methylcyclopentyl[c]	50	0.5		54	46
trans-2-Methylcyclopentyl[c]	50	0.5		06	94

[a]Anhydrous t-butyl alcohol saturated with urea was used, presumably elimination is completely solvolytic.

[b]Ref. (33).

[c]D. Wedegaertner, Dept. of Chemistry, Iowa State University, Ames, Iowa. Elimination of 2-methylcyclopentyl p-toluenesulfonates. Private communication. 1962.

with a second order elimination, one would expect an increase in the concentration of the base to decrease the overall (measured) rate constant. From the rate equation $k \text{ (measured)} = \frac{\text{rate}}{(B)} = k_1(S) + k_2(S)(B)$, one can

see that an increase in the base concentration (B) has no effect on the unimolecular rate, whereas the bimolecular (E2) rate is increased. Since the measured rate constant is second order (divided by the base concentration) and since the k_1 term remains constant at higher base concentrations, it is evident that although the overall rate of the reaction increases with increasing base concentration, the measured (overall) second order rate constant will decrease. This is, in fact, observed in the elimination of the 2-t-butylcyclopentyl p-toluenesulfonates. The competing unimolecular (solvolysis) process could not be completely suppressed, even at high base concentrations.

The equilibrium of the methylcyclopentenes has been shown to favor 1-methylcyclopentene. Treatment of 1-methylcyclopentene with benzyl sodium (liquid phase in an autoclave) at 250° yielded a mixture of 82% 1-olefin, 12% 3-olefin and 6% 4-olefin (126). It should be emphasized that these olefin ratios may not be the true equilibrium mixture, but only a reflection of the relative anion stabilities in this system. The preponderance of 1-olefin can be ascribed to a greater stability of the more substituted olefin and decreased methyl-hydrogen (steric) interactions relative to the other two isomers. The equilibrium ratio of the t-butylcyclopentenes should lie further on the side of 1-olefin, since steric interactions of the bulky t-butyl group with the cis-ring hydrogen atoms are lessened considerably when the t-butyl group occupies a trigonal position (lies in the plane of the cyclopentane ring). Also, the 3-t-butyl olefin should be more stable than the 4-t-butyl olefin since one adjacent t-butyl-hydrogen interaction is eliminated in the 3-olefin.

Solvolysis of cis-2-t-butylcyclopentyl p-toluenesulfonate in anhydrous t-butyl alcohol with urea or sodium acetate added to take up the excess acid formed yields 100% 1-t-butylcyclopentene, whereas the trans-2-isomer gives 95% 1-olefin and 5% 3-olefin. Hückel reported 91-100% 1-olefin from the solvolysis of the cis- and trans-2-methyl- and isopropylcyclopentyl p-toluenesulfonates in methanol (Table 2). Increasing the base concentration increases the rate of elimination relative to solvolysis which is manifested in the ratio of 3-olefin to 1-olefin. The E1 process is independent of the base concentration, except for a slight salt effect, whereas the E2 reaction is directly proportional to the base concentration. Elimination of cis-2-t-butylcyclopentyl p-toluenesulfonate in 1.38 M. potassium t-butoxide gives 65% 3-t-butylcyclopentene and 35% 1-olefin. Since solvolysis is undoubtedly present even at this base concentration, the maximum percentage of 1-olefin formed in a bimolecular elimination would be approximately 30%. Elimination (E2) in this system could be producing exclusively 3-olefin. The absence of 1-t-butylcyclopentene from the elimination of trans-2-t-butylcyclopentyl p-toluenesulfonate at high base concentrations indicates no cis-elimination is occurring in this system. The olefin ratios were determined by GPC and NMR. Isomerization of the olefins was shown not to occur under the reaction conditions. In other 2-substituted cyclopentyl systems that have been studied no solvolysis was evident in the 2-phenylcyclopentyl p-toluenesulfonates (32) whereas solvolysis is manifested from the olefinic product ratios in the elimination of the 2-methylcyclopentyl p-toluenesulfonates, even in 0.5 M. potassium t-butoxide/t-butyl alcohol at 50°.

A number of methods were used in an attempt to separate the rate constants, k_1 and k_2, for the unimolecular and bimolecular elimination reactions. The rate expression for the appearance of product from the competing reactions is $dx/dt = k_1(b-x) + k_2(b-x)(a-x)$, where (b-x) and (a-x) are the p-toluenesulfonate and base concentrations at time t. Plotting x versus t gives a curve, such that the slope of a line tangent to the curve at any time t gives the value of dx/dt. Dividing this value by (b-x) and plotting this against the base concentration (a-x) gives a straight line. The slope of this line is equal to k_2 and the intercept provides the value of k_1. This method was utilized by Young and Andrews (127) to calculate the rates of S_N1 and S_N2 hydrolysis of the butenyl chlorides. The data for the 2-t-butylcyclopentyl p-toluenesulfonates was not amenable to this method. The second order rate constants were extremely high and in most cases the intercept (k_1) was a negative number. The small change in the base concentration and the difficulty in determining dx/dt were probable sources of error. The above rate expression was integrated and k_1 was set equal to a constant (c) times k_2, thus assuming k_1 and k_2 do not change with the base concentration. The kinetic data was analyzed by use of a computer, varying c until the percentage error of the rate constant calculated from the individual kinetic points was minimized. Again, either the data wasn't precise or the assumption on minimizing the percentage error is invalid, as consistent and reproducible rates were not obtained.

Another method attempted was to assume that the E1 reaction does not consume base. Then, per cent E2 (3-olefin) = $\frac{k_2(B)}{k_2(B) + k_1}$ and a value of

k_2/k_1 can be determined from the experimental olefinic product ratio. Assuming E2 gives 100% 3-olefin and E1 gives 100% 1-olefin, the ratio of k_2/k_1 was calculated as 6.5 for trans-2-t-butylcyclopentyl p-toluenesulfonate and 0.64 for the cis-isomer using the olefin ratios at two base concentrations (0.1 and 0.3 M.). These ratios were not constant at higher concentrations of base. The bimolecular elimination rate could then be calculated from the measured second order rate constant and the ratio of k_2/k_1. Rate constants calculated in this manner were found to be dependent upon the initial base concentrations, thus $k_2 = 6.2 \times 10^{-4}$ at 0.1 M. base and 2.7×10^{-4} at 0.3 M. base for cis-2-t-butylcyclopentyl p-toluenesulfonate and $k_2 = 1.0 \times 10^{-4}$ at 0.1 M. base and 0.83×10^{-4} at 0.3 M. base for trans-2-t-butylcyclopentyl p-toluenesulfonate. Correcting each kinetic point in a reaction for the amount of base consumed by each process (E1 and E2) using the previously calculated ratios of k_2/k_1 and recalculating the rate constants gave slightly higher rate constants than those calculated above. Again the rate constants were dependent upon the initial base concentration. The primary source of error in these last two methods is in the calculation of the ratio of k_2/k_1. The initial base concentration is used along with the product olefin ratio determined at the infinity point. No correction is made for decrease of the base concentration with time resulting from the E1 and E2 reactions. Since the rate of the bimolecular reaction actually decreases with respect to the unimolecular process as the reaction proceeds, the values obtained above for k_2 should be high.

The most accurate and consistent rate constants were calculated assuming pseudo first order conditions---that the concentration of the base

doesn't change substantially during the course of the reaction. The measured second order rate constant was multiplied by the initial base concentration to give a pseudo first order rate constant. The solvolysis rate constant (k_1) can be directly calculated by multiplying this rate constant by the per cent olefin obtained from the E1 process. Multiplying the pseudo first order rate by the per cent olefin formed from the bimolecular elimination reaction and dividing by the base concentration gives k_2. The approximated individual rate constants (k_1 and k_2) for the 2-t-butylcyclopentyl p-toluenesulfonates are given in Table 14 along with the rates of elimination (E2) and solvolysis for other cyclopentyl compounds.

The values for k_2 were calculated from the observed rate constants measured at higher base concentrations (0.27-0.30 M.). Since a 5-10 mole excess of base was used in these eliminations and since the reactions were followed to 75% completion, pseudo first order conditions were approximated in these systems. The actual rate constants for the second order eliminations would be higher than those calculated if the effective base concentration decreased with time (pseudo first order conditions did not strictly apply at these conditions). No large amount of ether formation was evident in these reactions. If a small amount of substitution occurred in the solvolysis reaction, the calculated second order rate constants (k_2) would be slightly high and the solvolysis rate constants (k_1) would be on the low side, as these rates were calculated only from the olefin product ratios. The values of k_1 increased slightly as the initial base concentration was increased, thus in order to minimize the salt effects, this value was calculated for the eliminations at lower

Table 14. Rates of second order elimination and solvolysis for some cyclopentyl p-toluenesulfonates.

p-Toluenesulfonate	Base and/or solvent	Temp. (°C.)	$k_1 \times 10^5$	$k_2 \times 10^4$
cis-2-t-Butylcyclopentyl[a]	t-BuOK/t-buOH	50	15.2[b] (16.3)[c]	1.59[b] (1.11)[c]
trans-2-t-Butylcyclopentyl[a]	t-BuOK/t-buOH	50	0.85[d]	0.70[d]
Cyclopentyl	t-BuOK/t-buOH	50	---	1.90[e]
trans-2-Phenylcyclopentyl	t-BuOK/t-buOH	50	---	0.28[f]
cis-2-Isopropylcyclopentyl[g]	EtOH	40	7.7	---
trans-2-Isopropylcyclopentyl[g]	EtOH	40	1.1	---
Cyclopentyl[h]	MeOH	40	5.5	---
cis-2-Methylcyclopentyl[h]	MeOH	30	2.2	---
trans-2-Methylcyclopentyl[h]	MeOH	30	0.44	---

[a]Average of rate constants at 4 different base concentrations, these values are calculated assuming pseudo first order conditions and are approximate.

[b]Assuming E2 gives 70% 3-olefin and E1 gives 100% 1-olefin.

[c]Assuming E2 gives 100% 3-olefin and E1 gives 100% 1-olefin.

[d]Assuming E2 gives 100% 3-olefin and E1 gives 95% 1-olefin.

[e]Applying a statistical correction of two since there are two trans-protons available for removal.

[f]Calculated for 3-olefin formation (total of 9% of olefinic products), Ref. (32).

[g]Solvolysis data extracted from Table 1.

[h]Solvolysis data extracted from Table 2.

base concentrations.

The solvolysis rates (k_1) in this system compare favorably with those reported by Hückel for the 2-methyl- and isopropylcyclopentyl p-toluenesulfonates (Table 14). He observed a ratio (k_1 cis/k_1 trans) of 5.0 for the 2-methylcyclopentyl p-toluenesulfonates in methanol at 30° and a ratio of 7.0 for the 2-isopropylcyclopentyl p-toluenesulfonates in ethanol at 40°. One would predict that the t-butyl compounds should react at a faster rate than their isopropyl-counterparts, as the relief of steric interactions in the product relative to the substrate should be much greater for the bulky t-butyl group. Since these interactions are much more important in the cis-2-t-butylcyclopentyl p-toluenesulfonate relative to the trans-isomer and since the less polar solvent, t-butyl alcohol, should magnify any difference in reaction rate between the cis- and trans-compounds, the relative cis- to trans- rate ratio should be much larger for the 2-t-butylcyclopentyl p-toluenesulfonates relative to the corresponding methyl and isopropyl compounds. A ratio (k_1 cis/k_1 trans) of 18-19 was observed in this system. The value of k_1 for cis-2-t-butylcyclopentyl p-toluenesulfonate would lie between 15.2-16.3 x 10^{-5} and k_2 would be in the range of 1.11-1.59 x 10^{-4} depending upon the percentage of 1-olefin (0-30%) formed in the bimolecular elimination (E2) reaction. The relative E2 rates of the 2-substituted cyclopentyl compounds will be discussed later with the 3-substituted isomers.

The rate constants and olefinic product ratios from the potassium t-butoxide elimination of a number of 3-substituted cyclopentyl bromides and p-toluenesulfonates are reported in Table 15. It is apparent in these systems, in contrast to the elimination of the 2-t-butylcyclopentyl

Table 15. Kinetics and product analysis from the potassium t-butoxide/t-butyl alcohol elimination of 3-substituted cyclopentyl derivatives.

Compound	Temp. (°C.)	Base conc. (moles/liter)	$k_2 \times 10^4$	Per cent 3-olefin	Per cent 4-olefin
trans-3-Phenylcyclopentyl p-toluenesulfonate	50	0.11	2.61	31	69
	50	0.28	3.39	29	71
	70	0.11	16.4	31	69
	50	1.38		28	72
	50	t-buOH[a]		37	63
trans-3-t-Butylcyclopentyl p-toluenesulfonate	50	0.11	1.93	12	88
	70	0.11	13.1		
	50	0.30		11	89
	50	1.29		12	88
	50	t-buOH[a]		34	66
cis-3-t-Butylcyclopentyl p-toluenesulfonate	50	0.11	3.54	22	78
	50	0.30		22	78
	50	t-buOH[a]		45	55
Cyclopentyl p-toluenesulfonate	50	0.10	3.89		
Cyclopentyl bromide	50	0.10	1.82		
	70	0.11	12.1		
3-t-Butylcyclopentyl bromide[b]	50	0.11	0.965	14	86
	50	0.28	1.03	14	86
	70	0.11	6.30	13	87
	50	1.36		13	87
3-Phenylcyclopentyl bromide[c]	50	0.15	1.97	30	70
	30	0.13	0.367		

[a]Anhydrous t-butyl alcohol saturated with urea was used, presumably elimination is completely solvolytic.

[b]Kinetics run on a mixture containing approximately 70% of the trans-isomer, no break in the kinetic data or decrease in the rate constant with time (calculated at each point) was noted.

[c]Ref. (32), kinetics run on a mixture of unknown composition.

p-toluenesulfonates, that the only reaction present is a second order (bimolecular) elimination. The olefin ratios are constant within experimental error throughout a wide range of base concentrations, and as a result of salt effects the rate constants are increased slightly (1.1-1.3) using higher base concentrations. Under solvolytic (E1) conditions the olefin ratios were also shown to be different from those obtained in the E2 reactions.

Approximately the same ratio of 4-t-butylcyclopentene to 3-t-butylcyclopentene was observed in the solvolysis of the p-toluenesulfonate esters of trans-3-phenylcyclopentanol (63:37) and trans-3-t-butylcyclopentanol (66:34), whereas cis-3-t-butylcyclopentyl p-toluenesulfonate produces a 55:45 ratio of these olefins. Hückel has reported (Table 1) that trans-3-isopropylcyclopentyl p-toluenesulfonate yields a 55:45 ratio of 3-olefin to 4-olefin and the cis-isomer gives a 50:50 mixture of olefins upon methanolysis. He has also observed a relative rate ratio of 0.86 : 1.0 : 1.18 for the ethanolysis at 40° of cyclopentyl, trans-3-isopropylcyclopentyl and cis-3-isopropylcyclopentyl p-toluenesulfonates, respectively. Similarly, Lillien and Khaleeluddin (30) have found the relative rates of acetolysis at 45° of the p-toluenesulfonate esters of various cyclopentanols are as follows: 3-methylcyclopentyl 1.0, cyclopentyl 1.1, cis-3-t-butylcyclopentyl 1.23, and trans-3-t-butylcyclopentyl 1.30. This lack of solvolytic discrimination in contrast to the 2-isomers (vide supra) is ascribed to the lack of non-bonded repulsive driving forces in any of the compounds studied. Thus, if the envelope conformation is important in the cis-3-isomer and the half-chair conformation predominant

for the trans-3-isomer, both esters occupy quasi-equatorial positions and rates of solvolysis for the two isomers should be similar.

The olefin ratios from the solvolysis of trans-3-phenyl and cis- and trans-3-t-butylcyclopentyl p-toluenesulfonates in t-butyl alcohol indicate the absence of large steric and electronic effects in these systems. The predominance of 4-t-butylcyclopentene in these systems over the apparently more stable 3-t-butylcyclopentene (vide supra) may be a result of a large amount of solvent participation in the removal of the beta-hydrogen atom. This would account for the greater percentage 3-olefin formed from cis-3-t-butylcyclopentyl p-toluenesulfonate relative to the trans-isomer and the greater amount of 4-olefin formed from the 3-t-butylcyclopentyl p-toluenesulfonates in t-butyl alcohol relative to the 3-isopropyl compounds in methanol. The bulky t-butyl substituent should more effectively shield the 2-proton from attack of solvent and the less polar solvent (t-butyl alcohol) might decrease solvation of the tosyloxy-group thus enhancing the importance of proton removal and increasing the per cent 4-t-butylcyclopentene formed. An equilibrium mixture of olefins would be expected if a truly "free" carbonium ion could be formed.

The relative rates of elimination of 2- and 3-substituted cyclopentyl compounds toward the 3- and 4-carbon atoms are of interest in determining conformational effects in the cyclopentane ring. These calculated rates are reported in Table 16. From the table it is readily apparent that the rates of elimination of the substituted cyclopentyl bromides relative to cyclopentyl bromide are approximately the same as the relative rate ratios of the substituted cyclopentyl p-toluenesulfonates relative to cyclo-

Table 16. Relative rates of elimination to 3- and 4-olefins by a number of substituted cyclopentyl p-toluenesulfonates and bromides at 50° in 0.1 M. potassium t-butoxide/t-butyl alcohol.

Compound	Relative rates of formation[a] 3-olefin	4-olefin
trans-2-(4-Methylphenyl) cyclopentyl p-toluenesulfonate[b]	1.2	--
trans-2-Phenylcyclopentyl p-toluenesulfonate[b]	1.2	--
trans-2-t-Butylcyclopentyl p-toluenesulfonate	3.0	--
cis-2-t-Butylcyclopentyl p-toluenesulfonate	4.8	--
cis-3-t-Butylcyclopentyl p-toluenesulfonate	3.4	12.0
trans-3-t-Butylcyclopentyl p-toluenesulfonate	1.0	7.4
trans-3-Phenylcyclopentyl p-toluenesulfonate	3.5	7.8
Cyclopentyl p-toluenesulfonate[c]	8.3	8.3
Cyclopentyl bromide[c]	6.7 (8.4)[e]	6.7
3-t-Butylcyclopentyl bromide	1.0 (0.80)[d]	6.2
3-Phenylcyclopentyl bromide[b]	4.4	10.2
trans-2-Phenylcyclopentyl bromide	1.1[f] (1.4)[e]	--

[a]Relative rates for p-toluenesulfonates and bromides are calculated separately.

[b]Ref. (32).

[c]Applying a statistical correction of two since there are two trans-protons available for removal.

[d]Value in parenthesis is the relative rate of the trans-isomer after correction for 30% cis-isomer present---assuming the overall rate ratio of the cis- to trans-isomers is the same as in the p-toluenesulfonates (1.83).

[e]Values in parenthesis are relative ratios when corrected 3-t-butylcyclopentyl bromide is taken to be 1.0.

[f]Rate calculated from the difference between the titrimetric and UV rate constants.

pentyl p-toluenesulfonate. Thus, the rates of trans-3-phenyl- and t-butylcyclopentyl bromides (correcting for the cis-isomer present) to give 3- and 4-olefins and the rate of trans-2-phenylcyclopentyl bromide to produce 3-olefin relative to the unsubstituted cyclopentyl bromide are the same as the corresponding rate ratios in the p-toluenesulfonate compounds. These results indicate a change in leaving group does not substantially alter the conformation of the cyclopentane ring and that the transition states of the corresponding bromide and p-toluenesulfonate eliminations are probably very similar in these systems. This latter conclusion is also supported by the fact that the bromides and p-toluenesulfonates of the 3-phenyl- and t-butylcyclopentyl systems give the same ratio of 4-olefin to 3-olefin. If, for example, the bromide elimination were more concerted with a greater amount of double bond character in the transition state than the corresponding p-toluenesulfonate, one would expect the more stable olefin (3-olefin) to be formed at a faster rate and in a higher yield in the bromide elimination. The amount of charge buildup on the alpha- and beta-carbon atoms should also influence the relative rates and therefore the percentages of 3- and 4-olefin formation in these systems.

In the 2-substituted cyclopentyl p-toluenesulfonates the relative rates of elimination to give 3-olefin are trans-2-phenyl 1.0 trans-2-t-butyl 2.5, cis-2-t-butyl 4.0, and cyclopentyl (corrected for two available trans-protons) 6.9. The increased reactivity of the cis-2-t-butylcyclopentyl p-toluenesulfonate by a factor of 1.6 over the trans-2-t-butyl isomer can be explained by steric acceleration from the cis-tosyloxy group, unhindered approach by the base in attack of the trans-beta

proton, and conformational effects of the cyclopentane ring. In the envelope conformation (t-butyl substituent occupying the tip of the envelope flap) puckering in the cis-2-t-butylcyclopentyl p-toluenesulfonate increases the dihedral angle toward 180°, whereas puckering in the trans-p-toluenesulfonate decreases the dihedral angle. This should also decrease the rate of elimination relative to cis-isomer. The decreased rates of trans-2-phenyl- and t-butylcyclopentyl p-toluenesulfonate (6.9 and 2.8 respectively) relative to cyclopentyl p-toluenesulfonate can readily be interpreted on the basis of a moderate decrease in the dihedral angle resulting from puckering of the five-membered ring in an envelope conformation. If the dihedral angle between the trans-beta proton and the leaving group were to approach 180° in the transition state, the t-butyl or phenyl substituent would be forced into an axial position and very serious steric interactions would result. The fact that trans-2-phenylcyclopentyl p-toluenesulfonate reacts 2.5 times slower than the trans-2-t-butyl compound is undoubtedly a result of the decreased amount of carbon-oxygen bond breaking in the transition state due to the electron-withdrawing inductive effect of the phenyl group. An effect this large (through two sigma-bonds) might be expected in this system, since the transition state for elimination lies on the E1 side where C-O bond breaking provides the predominant driving force for the reaction. This inductive effect is also evident in trans-2-(4-methylphenyl) cyclopentyl p-toluenesulfonate which reacts slower than cyclopentyl p-toluenesulfonate by a factor of 6.9 and in trans-2-phenylcyclopentyl bromide which reacts approximately 6.1 times slower than cyclopentyl bromide. The relative reactivities of cyclopentyl p-toluenesulfonate and cis-2-t-butyl-

cyclopentyl p-toluenesulfonate (1.7:1) is a little more difficult to rationalize. One would predict a more favorable dihedral angle in the envelope conformation of the cis-2-t-butyl compound along with any steric acceleration resulting from eclipsing of the t-butyl and tosyloxy groups groups to increase the rate of elimination relative to the unsubstituted cyclopentyl compound. The observed decreased rate of the cis-2-t-butylcyclopentyl p-toluenesulfonate may be a result of steric hindrance to solvation of the tosyloxy group due to the bulk of cis-2-t-butyl substituent. This would render the p-toluenesulfonate a poorer leaving group and should thus decrease the reaction rate. Also, a half-chair conformation for the cis-2-t-butylcyclopentyl p-toluenesulfonate in which the t-butyl group occupies a quasi-equatorial position should be equal in energy to the envelope conformation. In this form the dihedral angle between the trans-3-proton and the tosyloxy group is decreased and the elimination rate would be smaller than for cyclopentyl p-toluenesulfonate.

It should be emphasized that although the differences in the relative rates of elimination in these systems are small, they are nevertheless real. Also, one would not expect large differences in these rates ---particularly in the 3-substituted cyclopentyl system. Conformational effects are also instrumental in affecting the rates of elimination of 3-substituted cyclopentyl compounds. It is profitable to compare the rates of elimination to form 3-olefin from both the 2- and 3-substituted compounds. The rate in these systems can be studied as a function of the relative positions of the beta-hydrogen atom and the leaving group, as olefin stability for a given transition state would be constant, since

the same olefin is produced from each isomer.

The relative elimination rates of the t-butylcyclopentyl p-toluenesulfonate to form 3-t-butylcyclopentene, trans-3-t-butyl 1.0, cis-3-t-butyl 3.4, trans-2-t-butyl 3.1, and cis-2-t-butyl 4.8, can be readily explained on the basis of steric interactions. cis-2-t-Butylcyclopentyl p-toluenesulfonate reacts the fastest as the trans-3-position (proton necessarily removed in trans-elimination) offers the least steric interference to the approach by base. Steric acceleration due to interactions between the cis-t-butyl and tosyloxy groups may account in part for this observed rate increase. The extraction of the proton cis to the t-butyl group in trans-3-t-butylcyclopentyl p-toluenesulfonate by t-butoxide would lead to the most serious steric interactions in the transition state, since this is the most hindered position, and consequently decrease the rate of elimination. The envelope and half-chair forms in which the t-butyl group occupies an equatorial position should be the lowest energy conformations for this isomer. In the envelope conformation puckering would increase the dihedral angle for elimination toward 180° and thus increase the reaction rate, whereas the reaction rate should be decreased in the half-chair form, since the dihedral angle is decreased (relative to the planar molecule) in this conformation. The reaction rate was the slowest of the t-butyl isomers, as would be predicted from steric hindrance to base attack and the half-chair conformation as the reacting form. The cis-3-t-butyl- and trans-2-t-butylcyclopentyl p-toluenesulfonates are intermediate in reactivity toward elimination. This is expected since any ring puckering should decrease the reaction rate, as the dihedral angle

is decreased relative to the planar ring structure, yet attack of base on the beta-hydrogen atom is unhindered relative to the trans-3-t-butyl isomer and more hindered than the attack on the cis-2-t-butyl isomer. The rates of these isomers are approximately equal with the cis-3-t-butyl compound reacting slightly faster (factor of 1.1). This indicates little difference in steric interactions, whether the potassium t-butoxide attacks the cis-3-hydrogen or the trans-2-hydrogen. The slight rate enhancement of the cis-3-isomer might be a result of better solvation of the equatorial 3-tosyloxy group in the transition state.

The fact that trans-3-phenylcyclopentyl p-toluenesulfonate eliminates 2.9 times as fast as the trans-2-phenyl ester is best explained on the basis of inductive effects. Since there should be little difference in solvation of the tosyloxy groups in these isomers, puckering of the cyclopentane ring should slightly favor elimination from the trans-3-compound and the cis-3-proton in the trans-2-phenyl compound should be much more susceptible to the attack of base, one might predict elimination of trans-2-phenylcyclopentyl p-toluenesulfonate to be favored slightly. The electron-withdrawing inductive effect of the phenyl substituent would decrease the amount of carbon-oxygen bond breaking (destabilize incipient carbonium ion formation) in the trans-2-phenyl isomer and decrease its rate of reaction, whereas it should increase the reaction rate of the trans-3-phenylcyclopentyl ester by increasing the stability of a beta-carbanion (increasing the beta-hydrogen acidity, thereby facilitating proton removal). Depending upon the amount of cis-isomer present in the reacting mixture, trans-3-phenylcyclopentyl bromide eliminates between 2.3 and 3.9 times faster than the trans-2-phenylcyclopentyl

isomer. This is in good agreement with the results obtained in the p-toluenesulfonate system. Comparing the phenyl substituted p-toluenesulfonates with the corresponding t-butyl esters also indicates an inductive effect associated with the phenyl group. The ratio of trans-2-t-butylcyclopentyl p-toluenesulfonate to the trans-2-phenyl isomer is 2.4 indicating an inductive deceleration by the phenyl substituent; whereas the ratio of trans-3-phenylcyclopentyl p-toluenesulfonate to the trans-3-t-butyl compound (3.5) suggests an acceleration by the phenyl group due to the inductive acidifying effect on the beta-proton. Since the bulky t-butyl group (relative to the phenyl group) more effectively shields the cis-2-proton from the attacking base, the decreased rate of the t-butyl compound in the latter system is undoubtedly due, in part, to this shielding effect. Again, the same effect is observed in the substituted cyclopentyl bromides, as trans-3-phenylcyclopentyl bromide reacts between 2.5 and 4.4 times faster than the corresponding trans-3-t-butyl isomer.

The relative rates of 3-substituted cyclopentyl p-toluenesulfonates to produce 4-olefin in potassium t-butoxide/t-butyl alcohol at 50° are as follows: trans-3-t-butyl 1.0, cis-3-t-butyl 1.6, trans-3-phenyl 1.05, and cyclopentyl 1.1. The rate of 4-olefin formation is between 2.2 and 7.4 times faster than the rate of 3-olefin formation from the 2- or 3-substituted cyclopentyl derivatives and approximately equal to the rate of elimination of the corresponding unsubstituted cyclopentyl compound. These results indicate very small steric and electronic factors are present in the elimination toward the 4-position in contrast to the results obtained in the formation of 3-olefin. Elimination to produce 4-olefin

probably proceeds through a transition state very similar to that of the unsubstituted compound. The 3-substituted cyclopentyl bromides eliminated in an analogous manner.

The fact that cis-3-t-butylcyclopentyl p-toluenesulfonate reacts 1.4 times faster than the unsubstituted cyclopentyl compound (corrected for a statistical factor of 2 protons) cannot be readily explained. Only in a half-chair conformation (t-butyl group occupying a quasi-equatorial position) is the dihedral angle increased toward 180°. This conformation should be slightly higher in energy than the envelope conformation with puckering at the 2-carbon atom. An increased stability of the 4-substituted olefin relative to the reacting p-toluenesulfonate in the transition state may account for the partial rate enhancement of the cis-3-substituted compound over the unsubstituted compound. It is also not certain that a correction for the statistical factor of two is completely valid for cyclopentyl p-toluenesulfonate. Once the base has approached the molecule, the presence of 2 protons in a position for reaction may not exactly double the rate. It should be pointed out that the overall rate of cis-3-t-butylcyclopentyl p-toluenesulfonate (3.54×10^{-4}) is less than that for cyclopentyl p-toluenesulfonate (3.89×10^{-4}), but the apparent increased reactivity toward elimination to give the 4-olefin is a result of the small amount of elimination toward the 2-position. Although it is beneficial to look at the rate of elimination into each branch one must also consider the overall rate constants of these compounds.

The enthalpies and entropies of activation for the above systems are recorded in Table 17. The activation parameters were calculated on an

Table 17. Enthalpies and entropies of activation for the elimination of 2- and 3-substituted cyclopentyl compounds at 50° in 0.1 M. potassium t-butoxide/t-butyl alcohol.

Compound	$\Delta H^{\ddagger}$ kcal./mole	$\Delta S^{\ddagger}$ cal./deg.-mole
trans-3-Phenylcyclopentyl p-toluenesulfonate	19.6 ± 0.8	-14.6 ± 2.5
trans-3-t-Butylcyclopentyl p-toluenesulfonate	20.1 ± 0.6	-13.4 ± 2.1
3-t-Butylcyclopentyl bromide	20.0 ± 0.8	-15.4 ± 2.4
Cyclopentyl bromide	19.5 ± 0.3	-15.3 ± 0.9
trans-2-t-Butylcyclopentyl p-toluenesulfonate	22.6 ± 1.0	- 6.9 ± 3.1
cis-2-t-Butylcyclopentyl p-toluenesulfonate	19.4 ± 0.7	-11.5 ± 2.2
trans-2-Phenylcyclopentyl bromide[a]	19.5 ± 0.5	-19.3 ± 1.5
trans-2-Phenylcyclopentyl p-toluenesulfonate[b]	17.6	-17.5

[a]Average of values calculated by computer from rate data at 30°, 50° and 70°.

[b]Ref. (33).

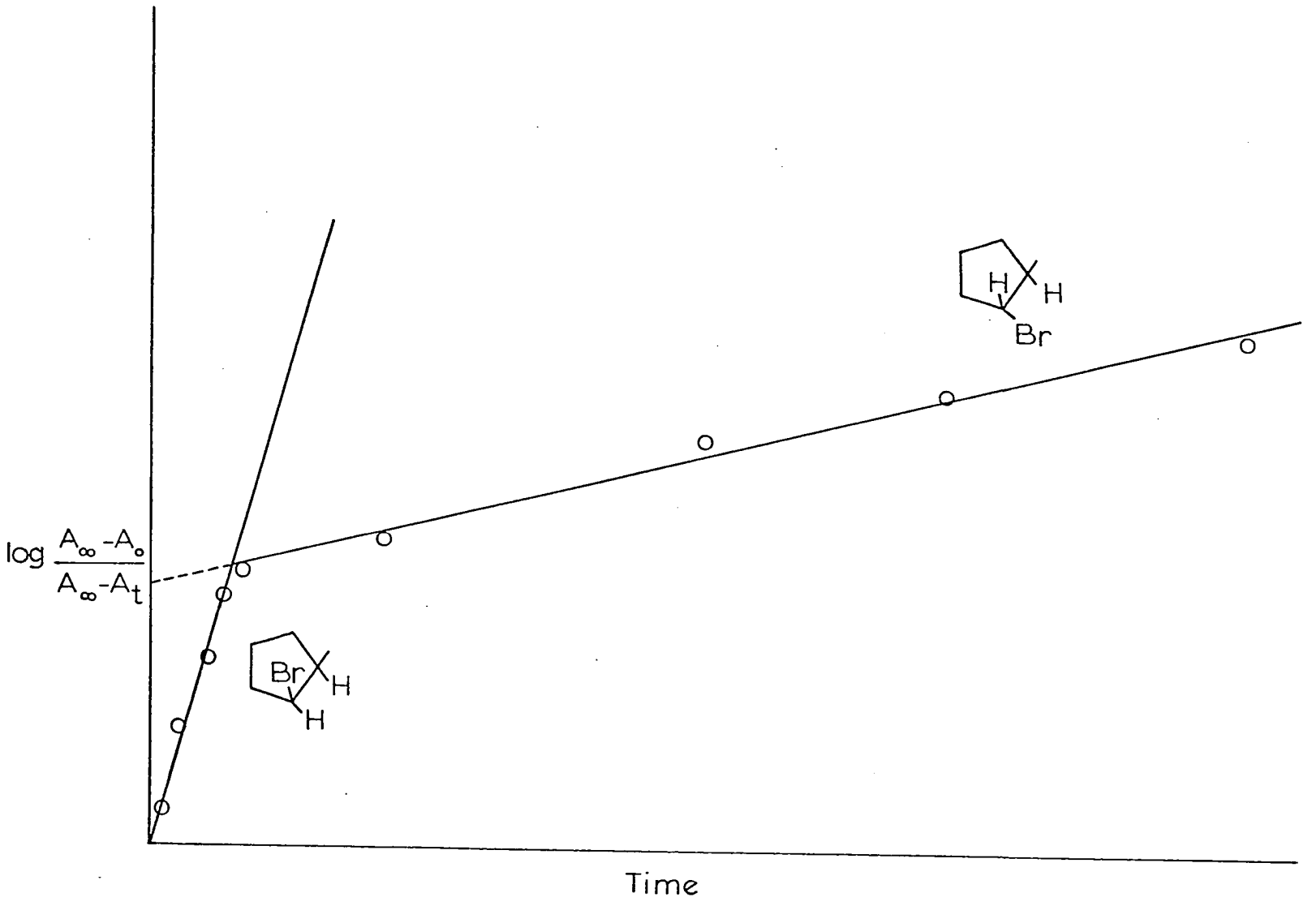
IBM 7074 computer using the rate constants measured at two temperatures, and the error term was calculated from the deviations in the respective rate constants. An examination of the enthalpies and entropies of activation indicates most of the systems studied have approximately the same values. The enthalpy values in general are larger and the entropy values are more positive than those previously reported for the beta-phenyl ethyl (81), 2-phenylcyclopentyl (32) and 1-phenyl-2-propyl (82) systems. This is consistent with a less concerted transition state---lying on the E1

side. More positive values of $\Delta S^{\ddagger}$ are evident in the cis- and trans-2-t-butylcyclopentyl p-toluenesulfonates where solvolysis was shown to be concurrent with elimination. The enthalpy for the cis-elimination of trans-2-phenylcyclopentyl bromide is approximately 2 kcal./mole higher in energy than that of the corresponding p-toluenesulfonate and the entropy value is nearly 2 cal./deg.-mole more negative. This indicates that the transition state for the cis-elimination of bromide is of higher energy and more concerted in nature than the p-toluenesulfonate.

The elimination rates of cis- and trans-2-phenylcyclopentyl bromide were determined from a mixture of the isomers using the method of differential reaction rates reported by Siggia and Hanna (128). This approach shown in Figure 5 utilizes the conventional plotting of the pseudo first order kinetic data. Since the elimination rates of the cis- and trans-isomers are greatly different, two straight lines can easily be drawn through the curve obtained. Extrapolation of the line representing the less reactive trans-2-phenylcyclopentyl bromide to zero time gives the initial concentration of the more reactive cis-bromide, and the infinity point for this elimination can thus be calculated. The data for the cis-2-phenylcyclopentyl bromide is then replotted using the calculated infinity point and the rate constant is obtained from the slope of the straight line obtained. The rate constant for trans-2-phenylcyclopentyl bromide is calculated from the slope of the line obtained using the first point after the calculated infinity point for the cis-isomer as the zero point.

A 77:23 mixture (measured by NMR) of trans- to cis-2-phenylcyclopentyl bromide was employed in these differential kinetic analyses.

Figure 5. Graphical determination of the rate constants for the elimination of cis- and trans-2-phenylcyclopentyl bromides from a mixture of the isomers.


log $\frac{A_\infty - A_o}{A_\infty - A_t}$
Time
Br
H
H
H
H
Br

Analysis of the product mixture after approximately 20% reaction by GPC and NMR indicated the cis-bromide was the faster reacting compound and this isomer produced only 1-phenylcyclopentene. From the product olefin ratio determined by GPC and the measured rate constants to produce 1-olefin and 3-olefin, and also from the ratios of the infinity points for the cis- and trans-bromides, the percentage cis- and trans-2-phenylcyclopentyl bromide in the starting mixture could be calculated. These values, ranging from 75-87% trans-bromide for the different runs, are in good agreement with that obtained from NMR. The second order rate constant for the isomerization of 3-phenylcyclopentene in 0.3 M. potassium t-butoxide at 70° was 5.34×10^{-6}. This is less than 2% of the value obtained for the cis-elimination of trans-2-phenylcyclopentyl bromide, and should not significantly affect the measured elimination rate of the trans-bromide through 80% reaction.

The rate constants for the elimination of cis- and trans-2-phenylcyclopentyl bromides along with the previously studied p-toluenesulfonates are reported in Table 18. The difference between the titrimetric and spectrophotometric (UV) rate constants for trans-2-phenylcyclopentyl bromide gives the rate constant for elimination toward the 3-hydrogen atom. This rate was previously discussed with the 2- and 3-substituted cyclopentyl bromides and p-toluenesulfonates (vide supra).

A large difference in the relative reactivities of these compounds is evident from the table. cis-2-Phenylcyclopentyl p-toluenesulfonate reacts 13 times faster than the trans-isomer at 30°, whereas cis-2-phenylcyclopentyl bromide eliminates faster than the trans-compound by a factor

Table 18. Rate constants for the elimination of cis- and trans-2-phenylcyclopentyl bromides and p-toluenesulfonates.

Compound	Temp. (°C.)	Base	Titrimetric rate	UV Rate (k_2)[a]
cis-2-Phenylcyclopentyl bromide	30	0.11 M. t-buOK	2.75×10^{-2}	2.41×10^{-2}
	30	0.27 M. EtONa		5.94×10^{-3}
trans-2-Phenylcyclopentyl bromide	30	0.11 M. t-buOK	7.62×10^{-6}[b]	3.89×10^{-6}
	50	0.11 M. t-buOK	4.34×10^{-5}[b]	2.85×10^{-5}
	70	0.11 M. t-buOK		1.96×10^{-4}
	70	0.29 M. t-buOK		2.10×10^{-4}
cis-2-Phenylcyclopentyl p-toluenesulfonate[c]	30	0.1 M. t-buOK		5.90×10^{-4}
	50	0.1 M. t-buOK		29.1×10^{-4}
	50	0.2 M. EtONa		24.2×10^{-4}
trans-2-Phenylcyclopentyl p-toluenesulfonate[c]	30	0.1 M. t-buOK		4.7×10^{-5}
	50	0.1 M. t-buOK		3.1×10^{-4}
	70	0.1 M. t-buOK		17.5×10^{-4}

[a]Second order rate constant calculated by dividing the base concentration into the measured pseudo first order rate constant---obtained from rate of 1-olefin production.

[b]Rate of concurrent 1-olefin and 3-olefin formation.

[c]Ref. (33).

of 6,200. This rate difference is due largely to the great reactivity of the cis-2-phenylcyclopentyl bromide, since it reacts 41 times faster than the corresponding cis-2-p-toluenesulfonate at 30°, although the cis-elimination from the trans-2-bromide is slower by a factor of 12 than that of the trans-tosyloxy compound. The sizable elimination rate of cis-2-

phenylcyclopentyl bromide is undoubtedly the result of a more concerted reaction than that of the corresponding p-toluenesulfonate, since the bromide is able to effectively remove negative charge from the beta-carbon atom in the transition state. The bromide elimination is thus shifted toward the central E2 region relative to the p-toluenesulfonate. In a cis-elimination the reaction transition state is probably shifted toward the ElcB side due to steric interference in attaining a cis-coplanar arrangement of the attacking base and the leaving group. Since a cis-elimination is inherently a less concerted reaction, one would predict that the rate of the bromide should slow down relative to the p-toluenesulfonate group. The fact that trans-2-phenylcyclopentyl p-toluenesulfonate eliminates 12 times faster than the corresponding bromide seems to indicate that the cis-elimination in this instance is not synchronous and that the transition state possesses considerable carbanionic character. The results do not rule out the possibility that the compounds in the latter case are reacting via the same transition state with the p-toluenesulfonate group being faster, whereas in the trans-elimination of the cis-2-phenylcyclopentyl compounds the bromide eliminates faster as a result of a much different transition state having a greater amount of El character (vide supra). A measurement of rho values and isotope effects in the 2-phenylcyclopentyl bromide elimination might help to distinguish between the above possibilities.

cis-2-Phenylcyclopentyl bromide eliminates 4.1 times faster in potassium t-butoxide/t-butyl alcohol than in sodium ethoxide/ethanol, which is approximately the same rate ratio (4.9) as was observed in the elimin-

ation of 1-phenyl-2-propyl bromide (82). The elimination of cis-2-phenylcyclopentyl p-toluenesulfonate proceeds faster in t-butoxide by a factor of only 1.2. The cis-elimination of trans-2-phenylcyclopentyl bromide proved too slow in sodium ethoxide/ethanol at 70° and solvolysis in the reaction was apparent. An interesting side light appeared in this solvolysis reaction, as a curved line was obtained plotting log $\frac{A_\infty - A_o}{A_\infty - A_t}$ versus time which could be divided into two straight line portions. Only the trans-2-phenylcyclopentyl bromide was present, as the cis-isomer eliminated under the reaction conditions (70°, 0.27 M. NaOEt, 20 minutes) prior to taking the zero point. The first order rate constants obtained spectrophotometrically for the two processes were 1.08×10^{-6} and 7.41×10^{-8}. The calculated infinity point was used in these determinations---assuming solvolysis should give mainly 1-olefin as was observed in other 2-substituted cyclopentyl compounds. The enthalpy of activation for the faster rate process was calculated as 20.8 kcal./mole and the entropy of activation was determined to be -25.6 eu. at 50°. The rate constant observed by Hückel for the ethanolysis of trans-2-isopropylcyclopentyl p-toluenesulfonate (Table 1) is approximately 100 times greater, correcting for temperature differences, than the faster rate constant observed for trans-2-phenylcyclopentyl bromide. Solvolysis of a 77:23 mixture of trans- to cis-2-phenylcyclopentyl bromides in 0.27 M. sodium acetate/absolute ethanol at 70° gave rate constants identical with those observed in sodium ethoxide within experimental error (1.04×10^{-6} and 7.07×10^{-8}). A possible explanation of the above results is that solvolyses of the cis- and trans-isomers are occurring at approximately the same rate

to give a carbonium ion which can either eliminate to form 1-phenylcyclopentene or rearrange to give a more stable benzylic carbonium ion by a 1,2-hydride shift. This carbonium ion could then react with solvent to form an ether which would solvolyze slowly to give the 1-olefin under the reaction conditions. The dual rates might also be a result of a mixture of 1- and 3-olefins formed in the solvolysis with subsequent rearrangement of the 3-olefin to give 1-olefin. This isomerization would be feasible in a strong base, but should not be prevalent in sodium acetate. Additional experimental data is needed to determine the solvolysis mechanism in this system. A check of the product formation during the reaction, a supplementary measurement of the rate of bromide ion formation, or the synthesis and solvolysis of the postulated ether intermediate would help in elucidating the mechanism of reaction.

Since very little work had been previously reported on the direction of elimination in ring systems other than the cyclohexyl compounds (83), the pyrolysis of differently substituted cyclopentyl acetates was studied. The per cent reaction, product olefin ratio and relative rates of elimination are given in Tables 19 through 21 for the pyrolysis of a number of 1,2- and 3-substituted cyclopentyl acetates at various temperatures. The absence of isomerization of the olefinic products under the reaction conditions was demonstrated by pyrolyses of the 3-olefins with an equimolar amount of anhydrous acetic acid.

Prior to a discussion of the results it should be pointed out again that conformational effects in these systems are very small at the high temperatures involved in acetate pyrolyses. The conformational equilib-

Table 19. Product ratio and percentage reaction as a function of temperature in the pyrolysis of 1- and 2-substituted cyclopentyl acetates.

Acetate	Temp. (°C.)	Per cent reaction[a]	Per cent 3-olefin	Per cent 1-olefin
Cyclopentyl	450	93		
	425	70		
	395	42		
	380	26		
1-t-Butylcyclopentyl	300	94		100
trans-2-Phenylcyclopentyl	500[b]	100	14	86
	425	98	13	87
	400	87	12	88
	380	63	11	89
	350	26	8	92
cis-2-Phenylcyclopentyl	500[b]	100	94	6
trans-2-Methylcyclopentyl[c]	465		37	63
trans-2-t-Butylcyclopentyl	450	100	16	84
	400	94	14	86
	380	64	13	87
	350	34	12	88
cis-2-t-Butylcyclopentyl	450	96	93	7
	425	83	95	5
	380	26	95	5

[a]Olefin percentages obtained by GPC and NMR.

[b]Ref. (89).

[c]D. Wedegaertner, Dept. of Chemistry, Iowa State University, Ames, Iowa. Pyrolysis of trans-2-methylcyclopentyl acetate. Private communication. 1962.

ria will be displaced toward the less stable forms and ground state conformation differences may not be very important at 400°. However, the

Table 20. Product ratio and percentage reaction as a function of temperature in the pyrolysis of 3-substituted cyclopentyl acetates.

Acetate	Temp. (°C.)	Per cent reaction[a]	Per cent 4-olefin	Per cent 3-olefin
cis-3-t-Butylcyclopentyl	497	100	30	70
	408	38	26	74
	358	10	25	75
trans-3-t-Butylcyclopentyl	496[b]	100	68	32
	409[b]	47	66	34
	500[c]	100	65	35
cis-3-Phenylcyclopentyl	408		29	71
trans-3-Phenylcyclopentyl	500[c]		50	50
	408[c]		48	52
	499[d]		52	48
	496[e]		50	50
cis-3-Isopropylcyclopentyl[f]	450		17	83
trans-3-Isopropylcyclopentyl[f]	450		57	43

[a]Olefin percentages obtained by GPC.

[b]Alcohol obtained from reduction of the trans-3-epoxide.

[c]Alcohol obtained from hydroboration of the 3-olefin.

[d]Alcohol obtained from reduction of the 4-epoxide.

[e]Alcohol obtained after 2 kinetic reductions of a mixture of 3-epoxides.

[f]Ref. (26).

steric factors which cause puckering, and therefore conformational differences in the ground state, will also be present in the transition state of these eliminations at the higher temperatures. It is these steric interactions which will affect the enthalpy and entropy of activa-

Table 21. Relative rates for the pyrolysis of the 2-t-butylcyclopentyl and 2-phenylcyclopentyl acetates.

Ratio of cyclopentyl acetates	Temp. (°C.)	Relative rate
trans-2-t-Butyl/trans-2-phenyl[a]	401	1.03
	371	1.05
	348	1.09
cis-2-t-Butyl/cis-2-phenyl[b]	367	4.70
	370[c]	5.08

[a]Calculated using chlorobenzene as an internal standard.

[b]Calculated using the initial and final ratios of the acetates and the per cent conversion of the 2-phenylcyclopentyl acetate to olefin.

[c]Pyrolysate was analyzed directly without prior extraction and work-up to minimize loss of the t-butyl acetate.

tion terms, and thus influence the relative pyrolysis rates. For example, a more bulky 2- or 3-substituent which would result in a greater puckering of the cyclopentane ring, due to increased steric interactions, and thus increase the conformational preference at room temperature, would also increase the activation energy for any pyrolytic process where eclipsing becomes more important in the transition state.

From the per cent reaction data in Tables 19 and 20, it is apparent that substitution in the five-membered ring in general decreases the rate of pyrolysis of a compound relative to unsubstituted cyclopentyl acetate, except in the case of the trans-2-substituted cyclopentyl acetates. Substitution thus appears slightly to decrease the rate of pyrolysis by increasing the steric interactions in the transition state. The per cent

reaction may be slightly low for the pyrolysis of cyclopentyl acetate because of the high volatility of cyclopentene, although precautions were taken to minimize the olefin loss. The nitrogen flow rate and reaction conditions of these pyrolyses were kept constant from one elimination to another. Although a comparison of the results obtained from separate pyrolyses are probably at best semi-quantitative, it appears from the competitive pyrolysis of trans-2-phenyl- and t-butylcyclopentyl acetates (Table 21) that extrapolation from one system to another (Table 19) is quite accurate.

The pyrolysis rate of cis-2-t-butylcyclopentyl acetate is approximately the same as that observed in cyclopentyl acetate; this must indicate that any decrease in rate by substitution of a t-butyl group on the ring is more than offset by an acceleration due to steric interactions between the cis-t-butyl and acetoxy groups. The increased rates of trans-2-phenyl- and t-butylcyclopentyl acetates over the unsubstituted compound may be readily explained by a large amount of double bond character in the transition state of the pyrolysis. More stable olefin formation (relative to the unsubstituted compounds) and decreased steric interactions in the transition state relative to the ground state would increase the pyrolysis rate. The large amount of 1-olefin formed relative to 3-olefin from the trans-2-substituted cyclopentyl acetates indicates double bond formation is the driving force for the direction of elimination (vide infra). Elimination toward the 1-position or 3-position in the trans-isomers should be equally favored on a statistical basis with any puckering of the ring system directing elimination toward the 3-

hydrogen atom. Pyrolysis of 1-t-butylcyclopentyl acetate appears to be more facile than 1-methylcyclopentyl acetate (129, 130), which also indicates a great amount of double bond character in the transition state, thus decreasing steric interactions between the t-butyl group and the beta-hydrogen atoms.

A comparison of the product ratios and relative rates of pyrolysis in the trans-2-substituted cyclopentyl acetates (Tables 19 and 21) illustrates the importance of steric and electronic factors in these reactions. The pyrolysis of trans-2-phenylcyclopentyl acetate and trans-2-t-butylcyclopentyl acetate are almost identical. The relative rates of these compounds are 1.03 at 400° (the t-butyl acetate reacts slightly faster) and the product ratios are almost identical, as the phenyl acetate produces 88% 1-olefin and the t-butyl compound gives 86% 1-olefin at 400°. Since the relative rate ratio changes very little over a 50° temperature range and since the 3-olefin ratio increases with temperature at approximately the same rate in each elimination, the activation energies for the pyrolysis of these compounds must be almost identical. From the change in product ratios with temperature it is apparent that the activation energy is higher for 3-olefin formation than for 1-olefin formation and that the activation energy is slightly higher in the case of trans-2-phenylcyclopentyl acetate relative to the corresponding t-butyl acetate. Calculation of the activation energy without knowing the absolute rate constant was attempted in these systems. An assumption that had to be made was that the residence time of the substrate on the column was constant throughout the temperature range studied. Then plotting log

(2.303 log 1/1-x) versus 1/T, where x is the percentage conversion measured by GPC and T is the absolute temperature, gives a straight line. The activation energy would be equal to the slope of the line times 2.303 R, where R is the gas constant (1.987 cal./deg.-mole). Activation energies for the systems in Table 18 calculated in this manner were 10-15 kcal./mole lower than those determined in acylic systems (82).

The fact that trans-2-t-butyl- and trans-2-phenylcyclopentyl acetates react in a similar manner is probably the result of two factors. Since the π-electrons of the benzene ring can conjugate with the developing p-orbital during the elimination of acetic acid and stabilize incipient olefin formations, one would predict that the phenyl substituted compound should have more double bond character in the transition state than the t-butyl acetate and would therefore give a much higher percentage of 1-olefin and react at a faster rate, as the transition state would be lower in energy. In the case of the 2-t-butylcyclopentyl acetate, however, double bond formation is favored over the 2-phenyl acetate as hybridization of the 2-carbon atom toward sp^2 in the transition state lowers the substituent into the plane of the ring and greatly decreases steric interactions with the ring hydrogens. This steric acceleration is much more important for a bulky t-butyl group and should increase the per cent 1-olefin formation (steric interactions remain present in transition state leading to 3-olefin) and also increase the rate of pyrolysis relative to the trans-2-phenyl acetate. These two effects must be of approximately equal magnitude to allow for the similarity of the transition states in these systems. The preponderance of 1-olefin over 3-olefin in

these pyrolyses indicates these factors are undoubtedly operant, since one would predict a small preference for 3-olefin formation on the basis of statistical and conformational effects (vide supra). In the pyrolysis of trans-2-methylcyclopentyl acetate the steric effect has been considerably reduced and one observes a similar reduction in the per cent 1-olefin produced (63% at 465°). Olefin formation in the transition state is likewise important in the trans-2-methyl compound, since the more stable olefinic product predominates.

Steric acceleration appears to be more important in the cis-2-substituted series, since cis-2-t-butylcyclopentyl acetate pyrolyzes faster than cis-2-phenylcyclopentyl acetate by a factor of 5.1 at 370° (Table 21). In this system steric interactions should be greater due to the cis-arrangement of the bulky t-butyl group and the acetoxy group. This should accelerate the removal of a molecule of acetic acid. From Table 19 it is apparent that 3-olefin formation is approximately 3 times faster (multiplying per cent reaction by per cent 3-olefin formed) in cis-2-t-butylcyclopentyl acetate than it is from the trans-2-t-butyl isomer. Also a large contribution to the low reactivity of the cis-2-phenyl acetate is the fact that resonance stabilization of incipient double bond formation is not possible in the cis-2-phenylcyclopentyl acetate, since the majority of the product is 3-olefin due to the availability of a cis-hydrogen atom in this position. One would, therefore, predict cis-2-t-butylcyclopentyl acetate should react much faster than the cis-2-phenyl compound. It should be pointed out that a factor of 5 is large under the reaction conditions at these high temperatures. The slower overall rate

of the cis-2-substituted acetates relative to the previously discussed trans-2-compounds is probably a result of the formation of the less stable 3-olefin in the transition state, since the trans-proton, leading to 1-olefin, is not available for cis-elimination.

The small amount of 1-olefin (4-6%) formed from the pyrolysis of cis-2-phenyl- and cis-2-t-butylcyclopentyl acetates cannot proceed by a concerted process since this would lead to a trans- double bond (an extremely high energy process). The absence of isomerization of the 3-olefin to 1-olefin was demonstrated under the reaction conditions. A small percentage of 1-olefin might result from contaminating trans-acetate, but NMR and GPC indicate that at least 3% of the 1-olefin is produced from the cis-isomer. The possibility that breakage of the carbon-oxygen bond occurs before that of the carbon-hydrogen bond must be considered in these systems. The reacting species, for a significant time interval, could exist as an intermediate ion or radical pair, depending upon whether the carbon-oxygen bond breaking was heterolytic or homolytic. Disproportionation of this intimate pair by hydrogen ion or hydrogen atom transfer in a subsequent step could produce 1-olefin (trans-elimination). Although this certainly is a higher energy process than a concerted elimination, both the homolytic (130) and heterolytic (87) reaction paths have been previously proposed in other systems.

The pyrolysis of the 3-substituted cyclopentyl acetates are recorded in Table 20. Hückel (26) reported in 1963 that the pyrolysis of cis-3-isopropylcyclopentyl acetate at 450° gave 83% of 3-isopropylcyclopentene, whereas pyrolysis of the trans-3-isomer produced 57% of the 4-olefin. He

attributed the ratio in the trans-3-acetate to the approximately equal probability of abstracting a cis-proton from the 2-carbon atom or the 4-carbon atom, whereas the cis-2-hydrogen in the cis-3-isomer is preferentially removed as steric crowding with the isopropyl group accelerates cleavage in this direction. cis-3-Phenylcyclopentyl acetate was found to produce 71% 3-phenylcyclopentene and the cis-3-t-butyl isomer gave 74% of the 3-olefin at 410°, whereas trans-3-phenylcyclopentyl acetate yielded approximately 52% of the 4-olefin and the trans-3-t-butyl compound produced 66% of 4-t-butylcyclopentene.

If a steric acceleration affecting removal of the 2-hydrogen atom is operant in the pyrolysis of cis-3-isopropylcyclopentyl acetate, one would have expected the cis-3-t-butyl isomer, due to its much greater bulk, to produce close to 100% of the 3-olefin. This was not the case. It should be noted that the olefin ratios reported by Hückel are suspect, since he purified his olefinic products by distillation from sodium prior to analysis. This may have isomerized the olefinic mixture. If product stability were important in directing elimination toward the 2-carbon atom in the cis-3-acetates, the trans-3-isomers should yield a greater percentage of 3-olefin, as the same driving force is present with less steric interactions in the transition state. Any puckering in the five-membered ring to relieve steric interactions would favor 4-olefin formation, since the dihedral angle between the acetoxy group and the 2-carbon hydrogen is increased.

Separation of the relative rates of pyrolysis at 410° by multiplying the per cent conversion times the per cent olefin formed in each branch

gives the following results. The relative rates of pyrolysis of the substituted cyclopentyl acetates to give 3-olefin are trans-2-t-butyl 1.0, trans-3-t-butyl 1.2, cis-3-t-butyl 2.2, and cis-2-t-butyl 5.8; the relative pyrolysis rates to give 4-t-butylcyclopentene are cis-3-t-butyl 1.0, and trans-3-t-butyl 3.1. Although these rates are approximate, since they were not measured in competitive pyrolyses and were in some cases extrapolated to 410°, they are in the right direction and give a good indication of the factors affecting the olefin ratios. It is not surprising that trans-2- and trans-3-t-butylcyclopentyl acetate pyrolyze to form 3-olefin at approximately the same rate, since the transition states for the two processes should be similar. The increased rate of cis-2-t-butylcyclopentyl acetate over the cis-3-isomer to give 3-olefin (factor of 2.6) can be explained by steric acceleration in the cis-2-acetate due to eclipsing of the t-butyl and acetoxy groups. The slight increase of 4-olefin with respect to 3-olefin upon raising the pyrolysis temperature indicates the activation energy is higher for the production of 4-olefin. A conformational effect must be present which results in the cis-3-t-butylcyclopentyl acetate (and similarly the other cis-3-substituted compounds) pyrolyzing to give 3-olefin 1.8 times faster than the trans-3-isomer. The trans-3-t-butylcyclopentyl acetate reacts 3.1 times faster than the cis-3-isomer in elimination toward the 4-proton and pyrolyzes faster overall by a factor of 1.2.

At the present time no explanation can be offered as to the source of these seemingly anomalous results obtained in the pyrolysis of the cis- and trans-3-substituted cyclopentyl acetates, although conformation-

al effects must be important in these eliminations. Further experimental work on the pyrolysis of the 3-methylcyclopentyl acetates and the determination of the equilibrium olefin mixtures in these systems may help elucidate the mechanism of these reactions.

EXPERIMENTAL

Preparation and Purification of Materials

All melting points and boiling points in this work are uncorrected and given in degrees Centigrade. Pressure is given in millimeters of mercury. The melting points were taken on a Fischer-Johns Melting Point Apparatus. The nuclear magnetic resonance spectra (NMR) were measured on either a Varian HR-60 or a Varian A-60 spectrometer using carbon tetrachloride as the solvent and tetramethylsilane (TMS) as an internal standard. The chemical shifts of protons in this thesis are given in ppm downfield from TMS (δ values). The multiplicity of these peaks is indicated by S (singlet), D (doublet), T (triplet), Q (quartet) and M (multiplet). These designations will be followed directly by the proton ratio, measured from the area integration of the respective peaks. The infrared spectra (IR) were measured neat, unless otherwise specified, either on a Perkin-Elmer Model 21 or a Perkin-Elmer Infra-Cord spectrometer. Mass spectra were measured on an Atlas CH4 mass spectrometer at 70 ev. with a recorder sensitivity of 3 volts. The major mass spectral peaks are given in mass/electron units. The number following in parenthesis is the relative height of that peak with the base peak being equal to 1. Microanalysis was performed either by Spang Microanalytical Laboratory, Ann Arbor, Michigan or Weiler and Strauss Microanalytical Laboratory, Oxford, England. Gas-liquid phase separations (GPC) were carried out using an F and M Model 500 Gas Phase Chromatograph with a thermal conductivity detector, unless otherwise stated. All peak areas were measured using an Ott

planimeter, and correction factors for differences in the thermal conductivity of most isomers were determined to be insignificant.

Syntheses

3-Chlorocyclopentene Freshly distilled cyclopentadiene (b.p. 41°, 321 gms., 4.86 moles) was cooled to -35° C. in a dry ice-acetone bath. Anhydrous hydrogen chloride was bubbled through the diene at a moderate rate, such that the temperature of the reaction mixture was maintained below -15°. The addition was stopped after five hours when a slight yellow color developed in the reaction liquid. The excess hydrogen chloride was removed by bubbling nitrogen through the system for one hour as the solution was warmed to room temperature. The compound was then placed on a Rotovac (rotary evaporator using aspirator vacuum) in an ice bath for five hours. When removal of the hydrogen chloride was complete the solution was a pale green in color. The 3-chlorocyclopentene formed (497 gms., 4.67 moles, 89% yield) was used immediately without further purification. This compound decomposes upon standing with evolution of hydrogen chloride.

NMR 2.44 (M,4), 4.94 (M,1), 5.91 (M,2).

3-t-Butylcyclopentene This compound was prepared by the addition of either t-butyl lithium in pentane or t-butyl magnesium chloride in ether to 3-chlorocyclopentene.

To 1.77 moles of t-butyl lithium (1.87 M. in pentane, Lithium Corporation of America) at -10° was added slowly with rapid stirring 210 gms. (2.05 moles) of 3-chlorocyclopentene diluted with 400 mls. of pentane. The mixture was allowed to react for two hours after addition was com-

plete and was then worked up by the slow addition of an equal volume of water to dissolve the lithium salts. The yellow water layer was extracted once with ether and the combined ether-pentane extracts were dried over anhydrous magnesium sulfate. The ether was evaporated and the compound was carefully distilled to give 30 gms. of pure 3-t-butylcyclopentene (b.p. 51-53°/36 mm., 14% yield based on t-butyl lithium).

t-Butyl Grignard reagent was prepared in a typical run by the slow addition of 300 gms. of t-butyl chloride (3.24 moles) to 79 gms. of magnesium turnings (3.24 moles) in four liters of diethyl ether. The difficulty encountered in starting this reaction was overcome by reacting the magnesium turnings with methyl iodide for a few minutes and then washing the metal twice with ether prior to use. The Grignard was allowed to react under nitrogen for three hours followed by addition at 0° of 260 gms. (2.54 moles) of 3-chlorocyclopentene diluted with 800 mls. of ether. This was allowed to react for two hours and the solution was poured into two liters of ice and 100 mls. of 10% sulfuric acid was added until the solution was acid to litmus paper. The water layer was extracted once more with ether and the combined ether extracts were washed once with a saturated sodium bicarbonate solution. It was found that extraction or refluxing with aqueous sodium hydroxide at this point removed a major portion of the contaminating 3-chlorocyclopentene. The organic layer was dried over magnesium sulfate and the ether was evaporated. Distillation gave 72 gms. of pure 3-t-butylcyclopentene (b.p. 52-53°/35 mm., lit. (94) b.p. 139°/760 mm., 18% yield based on t-butyl chloride).

NMR 0.84 (S,9), 1.80 and 2.29 (M,5), 5.66 (M,2).

GPC at 120° using a ten foot column of Ucon LB 550X on 35/80 mesh Chromosorb P indicates that the major impurities in the crude reaction mixture were 3-chlorocyclopentene, cyclopentadiene dimer, and another higher boiling peak---possibly a t-butyl dimer.

2- and 3-t-Butylcyclopentanols The t-butylcyclopentanols were prepared by hydroboration followed by basic hydrogen peroxide oxidation using the procedure of H. C. Brown and G. Zweifel (97). In a two liter three-necked flask flushed with nitrogen 50.6 gms. (0.41 mole) of 3-t-butylcyclopentene was added to 8.7 gms. of sodium borohydride (0.23 mole) in 425 mls. of diglyme (bis-2-methyoxyethyl ether, purchased from Aldrich Chemical Co.). After stirring for one hour 32.2 gms. (0.23 mole) of boron trifluoride etherate was slowly added at 0° and the solution was allowed to stir at room temperature for four hours. The solution was then cooled to 0° and 47 mls. of ice water was slowly added with a vigorous evolution of hydrogen gas. This was followed by addition of 430 mls. of 10% sodium hydroxide solution at a moderate rate. Hydrogen peroxide (328 mls. of a 30% solution) was then slowly added over a period of twenty minutes. The nitrogen atmosphere was then removed and the solution was allowed to react at room temperature for twelve hours. The solution was poured into one liter of ice water and the white suspension extracted four times with ether. The combined ether extracts were dried over magnesium sulfate and the ether was removed by evaporation. The alcohols were separated on a 30 in. (10 mm. internal diameter) Nester/Faust spinning spiral distillation column. Compositions of fractions from the distillation were monitored by GPC using a ten-foot Ucon LB 550X (1:10)

on 35/80 mesh Chromosorb P at a temperature of 160°.

GPC of the alcohols prior to distillation indicated the ratio of 2-t-butylcyclopentanol to 3-t-butylcyclopentanol was 65:35. Retention times of the alcohols were five minutes and seven minutes respectively. GPC of the 2-t-butylcyclopentanol formed from hydroboration showed only 2% of the cis-2-alcohol on a four foot LAC 446 (1:5) on 60/80 mesh Chromosorb W column at 130°. The ratio of trans- to cis-3-t-butylcyclopentanol was approximately 84:16, as was determined by GPC using a 100 meter Golay capillary column with a Silicon SE 30 liquid phase at 65°. Retention times were 40 min. and 38 min. respectively.

2-t-Butylcyclopentanol, b.p. 60°/5 mm. NMR 0.89 (S,9), 1.57 (M,7), 3.66 (S,1), 3.94 (M,1). Anal. Calculated for $C_9H_{18}O$: C, 76.00; H, 12.76. Found: C, 75.84; H, 12.62.

3-t-Butylcyclopentanol, b.p. 75°/5 mm. NMR 0.85 (S,9), 1.55 (M,7), 4.18 (M,1), 4.20 (S,1).

2- and 3-t-Butylcyclopentanols In order to increase the yield of 3-alcohol relative to 2-alcohol, hydroboration with a bulky diborane (triisopinocamphenyldiborane) was used according to the procedure of Brown and coworkers (132).

In a two liter three-necked flask flushed with nitrogen was placed 12.3 gms. (0.33 mole) of sodium borohydride in 205 mls. of purified tetrahydrofuran. The flask was immersed in an ice bath and 61 gms. (0.43 mole) of boron trifluoride etherate in 65 mls. of tetrahydrofuran added slowly. One hundred and eleven gms. (0.64 mole) of α-pinene (GPC indicates 6% of the β-isomer is present) in 105 mls. of tetrahydrofuran was

added and allowed to react for five hours at 0°. 3-t-Butylcyclopentene (24.3 gms., 0.196 mole, in 110 mls. of tetrahydrofuran) was then added and this was allowed to react at room temperature for sixteen hours. Ice water (30 mls.) was then added to decompose the residual hydride. The organoborane was oxidized at 0° by the addition of 110 mls. of 3 N. sodium hydroxide followed by the slow addition of 83 mls. of 30% hydrogen peroxide. The mixture was stirred for two hours and 30 mls. of water was then added followed by 90 gms. of solid potassium carbonate, which helped to separate aqueous and ether layers. The aqueous layer was then extracted once with tetrahydrofuran and once with diethyl ether. The solvent was evaporated and the alcohols were separated on a 30 in. (10 mm. internal diameter) Nester/Faust spinning band column. After distillation of the unreacted olefins and the alcohols was complete, it was noted that olefins distilled over when the column and pot temperatures were substantially increased. This was probably due to pyrolysis of unoxidized organoborane compounds carried over in the workup. NMR and GPC indicated the ratios of 1-, 3-, and 4-t-butylcyclopentenes formed from pyrolysis were 92:6:2 respectively. The yield of the purified t-butylcyclopentanols was 58%. GPC of the alcohols prior to distillation indicated the ratio of 2-t-butylcyclopentanol to 3-t-butylcyclopentanol in this reaction was 60:40 with 64% of all the alcohols being isopinocampheol.

The specific rotations of reactants and products were measured neat at 25° using the D line of sodium with an O. C. Rudolph polarimeter.

α-Pinene, $\alpha = +8.094^{\circ} \pm 0.015$. Optically pure $[\alpha]_D^{20} = +47.6^{\circ}$ (133).

Isopinocampheol, α* = -10.72° ± 0.04. Reported from hydroboration $[\alpha]_D^{20}$ (benzene) = -32.8° (133).

trans-2-t-Butylcyclopentanol, α= -1.297° ± 0.022.

3-t-Butylcyclopentanol, α= 0.00 (corrected for 2-t-butylcyclopentanol and isopinocampheol in sample from GPC area ratios).

3-t-Butylcyclopentanol The structure of 3-t-butylcyclopentanol was shown by its independent synthesis shown in Figure 1. The procedure of Allinger and Greenberg (134) was followed for the first five steps of the reaction. Commercially available 4-t-butylcyclohexanol was oxidized with sodium dichromate to give the corresponding ketone. The Baeyer-Villiger reaction was carried out on the crude ketone to give a 54% yield from the starting alcohol of γ-t-butyl-ϵ-caprolactone (b.p. 130-135°/2mm.). This was ring opened using 48% hydrobromic acid to give 4-t-butyl-6-bromohexanoic acid which was not isolated. Esterification of the acid with ethanol-sulfuric acid gave a 48% yield (from the lactone) of ethyl 4-t-butyl-6-bromohexanoate.

Ring closure was achieved by adding 60 mls. of a 0.4 M. potassium t-butoxide/t-butyl alcohol solution to 5.9 gms. (0.02 mole) of the bromo-ester and allowing to react overnight. After most of the t-butyl alcohol was stripped off on a rotovac, the residue was dissolved in water and extracted with ether. The ether layer was dried and the solution distilled to give 3-t-butylcarbethoxycyclopentane. b.p. 88-90°/2.5 mm., IR 5.76μ.

NMR 0.88 (S,9), 1.22 (T,3), 1.71 (M,7), 2.60 (M,1), 4.04 (Q,2).

---

*Measured at 20° in diethyl ether.

Anal. Calculated for $C_{12}H_{22}O_2$: C, 72.68%; H, 11.18%. Found: C, 72.57%; H, 11.24%. Saponification Equivalent. Calculated: 198.3. Found: 208.0.

The ester (2.5 gms.) was then saponified using 20 mls. of 0.8 N. sodium hydroxide in ethanol and refluxing for 20 hrs. After most of the ethanol was evaporated on a Rotovac, the aqueous layer was extracted with ether. Drying and distillation gave two gms. of 3-t-butylcyclopentane carboxylic acid (b.p. 95°/0.4 mm.). This was added to 25 mls. ether and reacted with 35 mls. of a filtered 0.72 N. methyl lithium solution for three hours. Excess hydrochloric acid (10%) was added and the aqueous layer was extracted with ether. The ether layer was then washed with a saturated sodium bicarbonate solution, dried and distilled to give 1.65 gms. (83% yield) of methyl 3-t-butylcyclopentyl ketone. b.p. 63-65°/ 2.1 mm. IR 5.96μ. The last three steps of the above synthesis were carried out by Dr. Gene F. Morris.

A solution of pertrifluoroacetic acid, made by the slow addition at 0° of one ml. of 90% hydrogen peroxide to 5.5 gms. (0.024 moles) of trifluoroacetic anhydride in 40 mls. of methylene chloride, was added to 1.65 gms. (0.0098 moles) of methyl 3-t-butylcyclopentyl ketone in 60 mls. of methylene chloride. After stirring at room temperature for five hours, forty mls. of saturated sodium carbonate was added until the solution tested neutral to hydrion paper. The aqueous layer was extracted three times with methylene chloride. The methylene chloride was evaporated and the 3-t-butylcyclopentyl acetate (IR 5.73) was directly saponified using ten mls. of 10% aqueous sodium hydroxide in 125 mls. of ethanol. After

refluxing for three hours, the solution was neutralized (hydrochloric acid) and 200 mls. of water was added. The aqueous layer was extracted four times with ether. The combined extracts were dried over magnesium sulfate and distilled to give 0.91 gms. (66% yield from the methyl ketone) of 3-t-butylcyclopentanol, b.p. 105°/15-17 mm.

NMR 0.85 (S,9), 1.55 (M,7), 4.18 (M,1), 4.43 (S,1).

GPC retention time was identical to that of the alcohol with the longer retention time synthesized from the hydroboration of 3-t-butylcyclopentene.

2- and 3-t-Butylcyclopentanone The 2- and 3-t-butylcyclopentanols synthesized from hydroboration were oxidized by the method of Jones (135) using chromic acid in acetone. In a typical run six mls. of Jones reagent, made by dissolving 26.72 gms. of chromium trioxide in 23 mls. of concentrated sulfuric acid and diluting to 100 mls. with water, was added dropwise at 0° to 3.11 gms. (0.022 mole) of the t-butylcyclopentanol in 200 mls. of reagent grade acetone. One ml. of Jones reagent is equivalent to 0.004 mole of alcohol. The solution turned from colorless to green and subsequently turned reddish-brown at the end point. After allowing the solution to react for two hours, most of the acetone was removed on a Rotovac and water was added to dissolve the chromium salts. The aqueous layer was extracted three times with a total of 300 mls. of ether. The combined ether extracts were dried with magnesium sulfate and the solution was distilled to give 2.41 gms. of ketone.

2-t-Butylcyclopentanone, b.p. 68-74°/13-15 mm. Yield 79%. NMR 0.95, (S,9), 1.82 and 1.97 (M,7).

3-t-Butylcyclopentanone, b.p. 84-93°/17 mm. Yield 89%. NMR 0.92 (S,9), 1.97 and 2.24 (M,7).

1-t-Butylcyclopentanol Treatment of cyclopentanone with t-butyl lithium produced 1-t-butylcyclopentanol in 14% yield. Forty-two gms. (0.50 mole) of cyclopentanone (purchased from Arapahoe Chemicals) in 200 mls. of dried ether was slowly added at 0° to 294 mls. of a 1.87 M. solution of t-butyl lithium in pentane (Lithium Corporation of America). Addition time was one hour and the reaction was allowed to proceed for an additional three hours. An equal volume of water was carefully added and the aqueous layer was extracted with ether. The combined ether extracts were dried over magnesium sulfate and the solution was concentrated. Distillation gave 10.3 gms. (14%) of 1-t-butylcyclopentanol, b.p. 75-85°/18 mm.

NMR 0.94 (S,9), 1.62 (M,8), 2.30 (S,1).

The attempted preparation of 1-t-butylcyclopentanol by the addition of cyclopentanone to t-butyl magnesium chloride resulted in none of the desired product.

1-t-Butylcyclopentene A catalytic amount (0.1 gm.) of p-toluenesulfonic acid was added to two gms. (0.014 mole) of 1-t-butylcyclopentanol in 15 mls. of benzene. This was refluxed for one hour and the water that formed was azeotroped and collected (0.25 ml.) in a Dean-Stark trap. The brown solution was then taken up in ether and was extracted once with a saturated sodium bicarbonate solution. After drying, the ether layer was concentrated and distilled to give 1.5 gms. (86%) of 1-t-butylcyclopentene.

NMR 1.04 (S,9), 1.88 and 2.22 (M,6), 5.27 (T,1). IR No -OH absorption.

1-Phenylcyclopentene This was prepared by acid catalyzed dehydration of 1-phenylcyclopentanol, which was prepared by reacting cyclopentanone with phenyl lithium.

Bromobenzene (157 gms., one mole, in 240 mls. of ether) was added over a period of one hour under nitrogen to 17.5 gms. (2.5 moles) of lithium wire in 240 mls. of ether. After reacting for two hours, one mole (84 gms.) of cyclopentanone in 250 mls. of ether was slowly added. This was allowed to react for three hours at room temperature. Water was then slowly added to the solution followed by 35 mls. of 10% sulfuric acid and the two layers were separated. The aqueous layer was extracted once with ether and the combined ether layers were extracted once with water. After drying over magnesium sulfate, the ether was evaporated. The residue was taken up in 200 mls. of benzene and 0.1 gm. of p-toluenesulfonic acid was added. The benzene (150 mls.) was then distilled to azeotrope the water formed (14 mls. collected, 18 mls. theoretical). The solution was cooled and ether was added. After one extraction with a saturated sodium bicarbonate solution, the ether layer was dried and concentrated on a steam bath. Distillation gave 87 gms. (61%) of pure 1-phenylcyclopentene, b.p. 68-71°/2 mm. (lit. (136) b.p. 118-121°/25 mm.)

NMR 1.86 and 2.52 (M,6), 6.00 (T,1), 7.19 (M,5).

trans-2-Phenylcyclopentanol Hydroboration (97) of 1-phenylcyclopentene produced the desired alcohol in 82% yield. Under a dry nitrogen atmosphere 12.8 gms. (0.34 mole) of sodium borohydride was dissolved with

86.2 gms. (0.60 mole) of 1-phenylcyclopentene in 600 mls. of diglyme. After stirring for one hour, 47.5 gms. (0.35 mole) of boron trifluoride etherate was added slowly at 0° over a period of thirty minutes. The reaction mixture was stirred at room temperature for three hours. Ice water (69 mls.) was then slowly added at 0° followed by the moderate addition of 630 mls. of 10% sodium hydroxide. After 480 mls. of 30% hydrogen peroxide were slowly added to the cold mixture, the solution was allowed to warm to room temperature and react for two hours. The mixture was then poured into two liters of ice water and the white suspension was extracted three times with ether. After drying over magnesium sulfate, the ether was removed by evaporation. Distillation gave 80 gms. of trans-2-phenylcyclopentanol, b.p. 90°/0.2 mm. (lit. (97) b.p. 110-113°/2 mm.).

NMR 1.75 (M,6), 2.70 (M,1), 3.09 (S,1), 3.92 (M,1), 7.11 (S,5).

Cyclopentanol Fifty gms. of cyclopentanone (0.59 mole) in 30 mls. of dried ether was added to 12 gms. (0.30 mole) of lithium aluminum hydride in 350 mls. of ether. Water was cautiously added after twelve hours to decompose the excess lithium aluminum hydride and this was followed by 10% hydrochloric acid. The aqueous layer (saturated with sodium chloride because of the high solubility of cyclopentanol) was extracted three times with ether and the combined ether layers were extracted once with a small amount of saturated sodium bicarbonate solution. The solution was dried and distilled to give 40 gms. (79%) of cyclopentanol, b.p. 78°/55 mm. (lit. (137) 139.8-140.4°).

NMR 1.61 (M,8), 4.14 (M,1), 4.24 (S,1).

Acetates All acetates were prepared from the corresponding alcohols by the action of acetyl chloride in benzene-pyridine solution. In a typical run one gm. of alcohol (0.007 mole) was dissolved in 15 mls. of benzene and 1.5 mls. (0.019 mole) of pyridine. The solution was cooled to 0° and two mls. (0.028 mole) of acetyl chloride was added with swirling, as an immediate white precipitate was formed. The solution was allowed to stand at room temperature from two to seven days. The mixture was then poured into ice-water and the benzene layer was separated. The aqueous layer was extracted once with ether and the combined extracts were dried over magnesium sulfate. Most of the benzene-ether was removed on a steam bath prior to vacuum distillation.

Cyclopentyl acetate, b.p. 30°/3 mm., NMR 1.6 (M,8), 1.93 (S,3), 5.08 (M,1). IR 5.74μ.

1-t-Butylcyclopentyl acetate reacted slower with acetyl chloride and had to be refluxed for 24 hours. NMR 0.94 (S,9), 1.48 and 2.00 (M,8), 1.88 (S,3). IR 5.75μ. GPC Acetate pyrolyzed on column at 150° to give mainly olefin.

trans-2-t-Butylcyclopentyl acetate, 12.3 gms. (92% yield), b.p. 38°/0.5 mm., NMR 0.89 (S,9), 1.61 (M,7), 1.93 (S,3), 4.98 (M,1). Anal. Calculated for $C_{11}H_{20}O_2$: C, 71.69%; H, 10.94%. Found: C, 70.93%; H, 10.68%.

cis-2-t-Butylcyclopentyl acetate, 2.7 gms. (84%), b.p. 69°/3 mm., NMR 0.96 (S,9), 1.68 (M,7), 1.93 (S,3), 5.20 (M,1), less than 4% of trans-2-acetate is present.

trans-2-Phenylcyclopentyl acetate, 5.2 gms. (92%), b.p. 95-98°/0.2 mm., NMR 1.77 and 2.08 (M,6), 1.86 (S,3), 3.08 (M,1), 5.05 (M,1), 7.14 (S,5). IR 5.73μ.

cis-2-Phenylcyclopentyl acetate, alcohol was prepared by J. S. Smith (32), 0.57 gms. (98%), b.p. 91°/0.4 mm., NMR 1.66 (S,3), 1.90 (M,6), 5.34 (M,1), 7.16 (S,5). IR (μ) 5.76, 8.14, 13.32, 14.62. GPC of alcohol indicated 6% of the trans-2-isomer was present.

trans-3-t-Butylcyclopentyl acetate, alcohol was prepared by catalytic hydrogenation of the trans-epoxide, 0.57 gms. (88%), b.p. 57°/0.6 mm., NMR 0.88 (S,9), 1.68 (M,7), 1.94 (S,3), 5.05 (M,1). IR 5.76μ.

trans-3-t-Butylcyclopentyl acetate, alcohol was prepared by hydroboration of 3-t-butylcyclopentene, 1.1 gms. (81%), b.p. 53°/0.5 mm., NMR 0.85 (S,9), 1.67 (M,7), 1.93 (S,3), 5.02 (M,1). IR 5.76μ.

cis-3-t-Butylcyclopentyl acetate, alcohol was prepared by catalytic hydrogenation of the cis-epoxide, 1.0 gms. (74%), b.p. 56°/0.6 mm., NMR 0.91 (S,9), 1.64 (M,7), 1.93 (S,3), 4.99 (M,1). IR 5.76μ.

cis-3-Phenylcyclopentyl acetate, alcohol was 95% pure and was prepared by Dr. Gene F. Morris from the kinetic reduction of a mixture of cis- and trans-3-phenylcyclopentene oxides using Raney nickel and hydrogen, 0.2 gm. (90%), b.p. 98°/0.45 mm., NMR 1.88 and 2.50 (M,6), 1.95 (S,3), 3.03 (M,1), 5.18 (M,1), 7.18 (S,5).

3-Phenylcyclopentyl acetate, alcohol prepared by hydroboration of 3-phenylcyclopentene by J. S. Smith (32), 1.22 gms. (98%), b.p. 93°/0.25 mm., NMR 1.79 and 2.08 (M,6), 1.95 (S,3), 3.21 (M,1), 5.21 (M,1), 7.15 (S,5). IR (μ) 5.76, 8.08, 13.45, 14.60.

trans-3-Phenylcyclopentyl acetate, alcohol was prepared by Dr. Gene F. Morris from reduction of 4-phenylcyclopentene oxide with hydrogen using Raney nickel as the catalyst, 0.1 gm., NMR 1.80 and 2.10 (M,6), 1.96 (S,3), 3.23 (broad M,1), 5.25 (M,1), 7.16 (S,5).

trans-3-Phenylcyclopentyl acetate, alcohol was prepared from the remaining epoxide after two kinetic reductions of a mixture of cis- and trans-3-phenylcyclopentene oxides with Raney nickel and hydrogen. NMR of the epoxide indicated the mixture contained greater than 90% of the trans-isomer.

p-Toluenesulfonates All p-toluenesulfonates were prepared from the corresponding alcohols using the procedure of Tipson (138). In an exemplary run two gms. of alcohol (0.014 mole) was dissolved in 20 mls. of pyridine and cooled to -5° in an ice-salt bath. Four gms. (0.021 mole) of p-toluenesulfonyl chloride (recrystallized twice from ether-pentane) was added rapidly and swirled until solution was affected. The reaction mixture was placed in the freezer (-20°) for three to seven days and during this time a precipitate of pyridine hydrochloride appeared. The solution was then poured into ice-water and the product generally crystallized in a short period of time. The solid was filtered and washed three times with cold 10% hydrochloric acid followed by three washings with cold water. The solid was then taken up in ether and dried over magnesium sulfate. In the cases where the ether was colored, Norite (animal charcoal) was added to the solution and the solution was heated and filtered. The ether was evaporated and the p-toluenesulfonates were recrystallized two to five times from an ether-pentane solvent mixture.

Yields in all cases ranged from 80-95%.

The compounds, which were liquids or didn't crystallize when they were poured into ice-water, were taken up in 150 mls. of ether and this solution was extracted three times with cold 10% hydrochloric acid followed by three extractions with cold water. The liquid p-toluenesulfonates were purified with Norite and after drying, all the solvent was removed in vacuo at 50°.

Cyclopentyl p-toluenesulfonate, m.p. 27°, Anal. Calculated for $C_{12}H_{16}SO_3$: C, 59.97%; H, 6.71%; S, 13.34%. Found: C, 59.77%; H, 7.11%; S, 13.39%.

trans-2-t-Butylcyclopentyl p-toluenesulfonate, alcohol from trans-epoxide reduction, m.p. 54-55°, NMR 0.81 (S,9), 1.24 and 1.67 (M,7), 2.44 (S,3), 4.69 (M,1), 7.50 (Q,4). Anal. Calculated for $C_{16}H_{24}SO_3$: C, 64.83; H, 8.16; S, 10.82. Found: C, 64.90; H, 8.21; S, 10.78. Compound decomposed during attempted vacuum drying at room temperature for three hours.

cis-2-t-Butylcyclopentyl p-toluenesulfonate, alcohol prepared from lithium aluminum hydride reduction of cis-epoxide, m.p. 91-95° (decomposition starts at 52°). NMR 0.91 (S,9), 1.67 (M,7), 2.44 (S,3), 5.03 (M,1), 7.50 (Q,4). Compound decomposed upon standing at room temperature for three days, though stable for months in the freezer (-20°).

trans-3-t-Butylcyclopentyl p-toluenesulfonate, alcohol prepared from hydroboration of 3-t-butylcyclopentene, liquid, NMR 0.82 (S,9), 1.76 (M,7), 2.43 (S,3), 4.84 (M,1), 7.48 (Q,4). IR 7.65μ and 8.50μ (KBr). Anal. Calculated for $C_{16}H_{24}SO_3$: C, 64.83; H, 8.16; S, 10.82. Found: C, 64.81; H, 7.91; S, 10.80. Compound decomposed after 12 hrs. at 60°

and 0.2 mm.

cis-3-t-Butylcyclopentyl p-toluenesulfonate, alcohol prepared from reduction of cis-epoxide, liquid, NMR 0.84 (S,9), 1.64 (M,7), 2.43 (S,3), 4.79 (M,1), 7.47 (Q,4). Anal. Calculated for $C_{16}H_{24}SO_3$: C, 64.83; H, 8.16; S, 10.82. Found: C, 65.07; H, 8.06; S, 10.80.

trans-3-Phenylcyclopentyl p-toluenesulfonate, alcohol prepared from hydroboration, m.p. 36-37°, NMR 2.00 (M,6), 2.42 (S,3), 3.13 (M,1), 5.05 (M,1), 7.12 (S,5), 7.52 (Q,4). Anal. Calculated for $C_{18}H_{20}SO_3$: C, 68.33; H, 6.37; S, 10.13. Found: C, 68.39; H, 6.09; S, 10.16.

Cyclopentyl chloride Cyclopentyl chloride purchased from Arapahoe Chemicals Inc., was dried over anhydrous magnesium sulfate and then distilled at 112°/760 mm. (lit. (137) b.p. 111-112°).

NMR 1.94 (M,8), 4.34 (M,1).

Cyclopentyl bromide Phosphorous tribromide (23.6 gms., 0.087 mole) was slowly added to 15 gms. of cyclopentanol, which had been previously flushed with nitrogen and cooled to -10° in an ice-salt bath. The mixture was allowed to warm to room temperature and react for sixteen hours. The solution was then poured into ice-water and extracted three times with ether after the aqueous layer was saturated with sodium chloride. The combined ether extracts were washed twice with saturated sodium bicarbonate and then dried over magnesium sulfate. Distillation gave 21 gms. (82%) of cyclopentyl bromide, b.p. 64°/60 mm. (lit. (137) b.p. 58-58.5°/50 mm).

NMR 1.92 (M,8), 4.36 (M,1). GPC on a ten-foot Ucon column gave three peaks, the relative areas being dependent upon the column and in-

jection port temperatures. Two of the peaks corresponded to cyclopentene and cyclopentyl bromide. The other peak was possibly a dimer or dicyclopentyl ether.

3-t-Butylcyclopentyl bromide Two grams (0.014 mole) of 3-t-butylcyclopentanol (prepared by hydroboration) was added to a mixture of 7.3 gms. (0.084 mole) of anhydrous lithium bromide and 10 mls. of 48% hydrobromic acid. This was allowed to stir for 12 hours at 67°. The dark brown mixture was then taken up in 100 mls. of ether and this was extracted three times with a total of 250 mls. of water. The ether layer was dried over magnesium sulfate and most of the ether was evaporated. The compound was eluted with Skelly A (a total of 500 mls.) from a four inch silica gel column. The Skelly A was evaporated on a Rotovac and 2.2 gms. (76%) of the 3-t-butylcyclopentyl bromide were collected without further purification. The compound gave an immediate precipitate of silver bromide with an alcoholic silver nitrate solution.

NMR 0.90 (S,9), 1.75 and 2.04 (M,7), 4.19 (M,1). GPC on a ten-foot Ucon column at 140° indicates only the bromide (retention time 3.2 minutes). Anal. Calculated for $C_9H_{17}Br$: C, 52.69; H, 8.35; Br, 38.95. Found: C, 52.37; H, 8.10; Br, 39.25.

Attempted preparation of trans-2-t-butylcyclopentyl bromide Ten gms. (0.115 mole) of lithium bromide was added to 2.8 gms. (0.197 mole) of trans-2-t-butylcyclopentanol (prepared by reduction of trans-epoxide with lithium aluminum hydride), followed by the addition of 13.5 mls. of 48% hydrobromic acid. The mixture, which turned reddish-brown almost immediately, was stirred at 65° for three hours and then an additional

sixteen hours at 50°. The dark brown mixture was then taken up in 75 mls. of ether and the organic layer was extracted four times with water. After drying over magnesium sulfate, the ether was evaporated and the solution was distilled under vacuum. The compound solidified in the condenser and had to be driven over by heating with a bunsen burner. This caused a slight amount of decomposition to occur.

The compound reacted rapidly with ethanolic silver nitrate to give a precipitate of silver bromide and had a melting point of 87-92° after a slight amount of compound liquified at 64°. Purification was accomplished by sublimation at 60° and 15 mm.

NMR 1.03 (S,3), 1.15 (S,3), 1.57 and 1.92 (M,8), 1.75 (S,3). A double resonance experiment (irradiating from 1.5 to 2.0 ppm) failed to collapse the two methyl peaks (1.03 and 1.15) separated by 8 cps.

IR (cm^{-1}) 1468 and 1450; 1389, 1375 and 1364; 1152, (CCl_4).

Anal. Calculated for $C_9H_{17}Br$: C, 52.69; H, 8.35; Br, 38.95. Found: C, 52.82; H, 7.99; Br, 39.22.

Mass Spectra 124 (0.19), 109 (base peak), 81 (0.24), 68 (0.28), 67 (0.69), 57 (0.27), 55 (0.26) and 41.2 (metastable ion).

Reaction of lithium bromide and hydrobromic acid (48%) with trans-2-t-butylcyclopentanol for 19 hrs. at 52° followed by elution chromatography through a short silica gel column with Skelly A gave a mixture of two compounds. One appeared to be 2-t-butylcyclopentyl bromide and the other was identical to the rearranged compound formed above.

NMR peaks at 0.98-1.03, 1.12, 1.54, 1.76, 1.91, 5.23.

The similar reaction of cis-2-t-butylcyclopentanol at 55° for 18 hrs.

gave the same compounds as the trans-isomer.

NMR peaks at 0.98, 1.03, 1.15, 1.55, 1.75, 1.93, 5.28.

Elimination of the rearranged bromide (0.3 gms.) was affected by reacting for 70 hours at 70° with 50 mls. of a 0.1 N. potassium t-butoxide/ t-butyl alcohol solution. After the mixture was neutralized with 1 N. hydrochloric acid, it was taken up in 150 mls. of carbon tetrachloride. This was extracted three times with a total of 600 mls. of water. The organic layer was then dried over magnesium sulfate, and the carbon tetrachloride was evaporated using a Rotovac. Spectra were taken directly of the filtered residue.

NMR 0.82 and 0.87 (S,12), 1.00 (S,8), 1.07 (S,15), 1.55 and 2.14 (M,50), 4.57 (S,4.2), 4.76 (M,1.0), 5.21 (M,1.9), 5.59 (S,1.3), 7.50 (Q,4.1). The numbers following the designations for the peak multiplicity are the relative areas of the respective peaks.

IR (cm^{-1}) 1450 (2), 1365 (3), 1256, 1178 (2), 1095, 1015, (CCl_4). The numbers in parenthesis following the frequency designations indicate the number of peaks occurring in that region.

GPC on a 25 ft. bis (ethyl hexyl) tetrachlorophthalate column at 100° indicated 5 olefins were present. The relative percentages and retention times are as follows: 1-t-butylcyclopentene, 18.5 min., 15%; 3-t-butylcyclopentene, 20 min., 4%; 21.5 min., 7%; 22.5 min., 39%; 25 min., 37%. The elimination of the bromide mixture prepared from cis-2-t-butylcyclopentanol with 0.3 M. potassium t-butoxide at 65° for 4 days gave the same olefins in the following percentages: 18.5 min., 0.6%; 20 min., 1%; 21.5 min., 1%; 22.5 min., 8%; 25 min., 90%.

cis- and trans-2-Phenylcyclopentyl bromides trans-2-Phenylcyclopentanol (6.0 gms., 0.037 mole) was added to a mixture of 25.5 gms. (0.283 mole) of anhydrous lithium bromide and 36.8 mls. of 48% hydrobromic acid. This was stirred at 70° for 15 hours. The solution turned red in color followed by a deep purple. The mixture was then taken up in 200 mls. of ether and was extracted three times with a total of 300 mls. of cold water. The ether layer was then dried over magnesium sulfate and the ether was removed under aspirator vacuum using a Rotovac. Vacuum distillation gave 6.1 gms. (76%) of the bromides, b.p. 75-85°/0.35 mm. Decomposition of the bromides, especially the cis-isomer, to the olefins was noted on distillation. In subsequent reactions elution chromatography was used to purify the bromides. trans-2-Phenylcyclopentyl bromide was eluted with Skelly A through a 14 in. silica gel column, this was followed by the pure cis-isomer. The products from chromatography, in contrast to distillation, contained no contaminating olefins. NMR and GPC on the bromides before fractionation indicated that the trans to cis ratio was 74/26.

NMR 2.04 (M,6), 3.24 (M,1), 4.08 (M,trans*), 4.59 (M,cis), 7.16 (S,5).

Anal. Calculated for $C_{11}H_{13}Br$: C, 58.68; H, 5.82; Br, 35.50. Found: C, 58.46; H, 5.76; Br, 35.45.

When cis-2-phenylcyclopentanol (2 gms.) was treated with lithium bromide/hydrobromic acid using the above procedure, the bromides (after

---

*Proton on the carbon atom bearing bromine.

distillation) were isolated in 15% yield. NMR indicated the ratio of trans-bromide to cis-bromide was 75/25.

The attempted preparation of cis-2-phenylcyclopentyl bromide by bubbling gaseous hydrogen bromide through a solution of 2 gms. of cis-2-phenylcyclopentanol in 50 mls. of pentane and 30 mls. of ether at -50° (dry ice-acetone bath) for one hour resulted only in the isolation of starting material.

The method of Wiley and coworkers (116) using triphenylphosphine oxide and bromine was also attempted. Bromine was added dropwise to 1.8 gms. of triphenylphosphine in 6 mls. of acetonitrile until the red-brown color persisted. One gram (0.006 mole) of trans-2-phenylcyclopentanol was then added at a moderate rate and the solution was allowed to stir for 30 minutes. Cold water (30 mls.) was then added and the solution was extracted with ether. The ether was dried over magnesium sulfate and the solution was micro-distilled to give less than 30% yield of the desired bromide. IR and NMR showed that starting material and olefin were the major contaminants. NMR of the bromides indicated the trans/cis ratio was 53/47.

The above procedure was repeated using dimethyl formamide (DMF, distilled from barium oxide, 46° (12 mm.) as the solvent, but this resulted only in isolation of phenylcyclopentene.

1-Trimethylsiloxy-3-t-butylcyclopentane The procedure reported by Langer, Connell, and Wender (139) was used with small modification for the preparation of the silyl ether. One ml. of hexamethyldisilazane (HMDS, Peninsular Chem. Research Inc.) and a catalytic amount (5 drops)

of trimethylchlorosilane (General Electric, dried over sodium sulfate and distilled at 57°) was added to 0.1 gm. of 3-t-butylcyclopentanol (0.0007 mole, prepared from lithium aluminum hydride reduction of the 3-ketone) in 10 mls. of carbon tetrachloride. After refluxing at 85° for 24 hours most of the carbon tetrachloride was removed on a steam bath.

NMR 0.08 (S,9), 0.84 (S,9), 1.51 (M,7), 4.10 (M,1). GPC using a 10 foot Ucon LB 550X column at 150° gave only one peak with a retention time 9 minutes less than the corresponding alcohol.

p-Nitrobenzoyl chloride Thionyl chloride (25 mls.) was added to 25 gms. (0.15 mole) of p-nitrobenzoic acid. This was refluxed on a steam bath for two hours, until all the acid had dissolved. The excess thionyl chloride was removed on a Rotovac at 100°. The solid was recrystallized twice from carbon tetrachloride to give pure p-nitrobenzoyl chloride, m.p. 72-73° (lit. (140) m.p. 73°). The crystals were stored prior to use at 0° under Skelly A in a desiccator.

trans- and cis-3-t-Butylcyclopentyl p-nitrobenzoates p-Nitrobenzoyl chloride (0.8 gms., 0.0043 mole) was added at 0° to 0.5 gms. (0.0035 mole) cis- or trans-3-t-butylcyclopentanol (prepared from reduction of corresponding epoxide) dissolved in 10 mls. of benzene and one ml. of pyridine. This was refluxed on a steam bath for 30 minutes and then allowed to react at room temperature for 24 hours. The mixture was then poured into ice-water and 100 mls. of ether was added. The separated organic layer was extracted four times with a saturated sodium bicarbonate solution. The ether was evaporated on a steam bath and the residue was recrystallized twice from ethanol-water.

trans-3-t-Butylcyclopentyl p-nitrobenzoate, m.p. 64-65°, NMR 0.91 (S,9), 1.24 (M,1), 1.83 (M,6), 5.35 (M,1), 8.20 (M,4). IR (μ) 5.85, 6.23, 6.55 and 7.41, 7.78, 14.00 (KBr).

cis-3-t-Butylcyclopentyl p-nitrobenzoate, m.p. 33-38° (NMR indicated some alcohol was present), NMR 0.93 (S,9), 1.25 and 1.67 (M,7), 5.32 (M,1), 8.18 (M,4).

Monoperoxyphthalic acid A modified procedure of Royals and Harrell (141) was used for the peracid preparation. In a flask cooled to -5° (ice-salt bath) is added 53 gms. (0.5 mole) of sodium carbonate and 250 mls. of water. Eighty mls. of cold 30% hydrogen peroxide was added, followed by 74 gms. (0.5 mole) of finely ground phthalic anhydride. After stirring at 0° for one hour, the mixture was added to 350 mls. of ether in a separatory funnel and 205 gms. of a 25% sulfuric acid solution was cautiously added. The ether layer was separated and the aqueous layer was extracted twice with 150 mls. of ether. The combined ether extracts were washed twice with 150 mls. of a 40% ammonium sulfate solution. The peracid solution was dried over anhydrous magnesium sulfate and stored in the refrigerator.

The solution was standardized prior to use by adding a 5 ml. aliquot of the ethereal solution to a mixture of 3 gms. of potassium iodide and 10 mls. of 1 N. hydrochloric acid in 75 mls. of water. This was titrated with standardized sodium thiosulfate solution until the reddish-brown iodine color disappeared to give a yellow solution. Ether was then added, followed by the addition of a few drops of 1% starch solution. This was titrated to the initial change of the dark purple solution to colorless.

Trifluoroperacetic acid This peracid was generated immediately before use by the slow addition of 5.7 mls. (0.04 mole) of trifluoroacetic anhydride to a suspension of 1.1 mls. (0.04 mole) of 90% hydrogen peroxide in ten mls. of methylene chloride at 0°. This was stirred for 20 minutes and then immediately transferred to an additional funnel and added dropwise to a mixture of 0.024 mole of olefin and sodium carbonate in methylene chloride.

Epoxidation

With m-chloroperbenzoic acid 3-t-Butylcyclopentene (117.2 gms., 0.95 mole) is slowly added to 270 gms. (1.35 moles) of m-chloroperbenzoic acid (85% active, FMC Corporation) in 2.7 liters of ether at 0°. This was allowed to warm to room temperature and react for 4 days. Saturated sodium bicarbonate (1.8 liters) was then added and this was allowed to stir for one hour. The ether layer was then extracted four more times with saturated sodium bicarbonate (until carbon dioxide evolution ceased), followed by one extraction with water. The combined aqueous layers were extracted once with ether, and the combined ether layers were dried over magnesium sulfate. The ether was removed under reduced pressure and the cis- and trans-3-t-butylcyclopentene oxides were separated by two successive distillations on either a 30 in. (10 mm. internal diameter) Nester/Faust spinning band column or a 4 foot glass helices packed, jacketed Todd column. The Todd column was found to be more efficient for larger quantities of epoxides (over 50 gms.). Fractions (ranging from one to five grams) were monitored by gas liquid phase chromotography using a 10 foot Ucon LB 550X column at 145°. Eighty per cent yield of

total epoxides for the above run was isolated after the two distillations. Approximately 25 gms. of cis-epoxide (97% purity, 75% recovery) and 75 gms. of trans-epoxide (99^{+}% purity, 60% recovery) were collected. GPC of the reaction product prior to distillation indicated only 2% of olefin remained and the ratio of trans-epoxide to cis-epoxide was 78/22.

cis-3-t-Butylcyclopentene oxide, b.p. 67°/18 mm., NMR 1.00 (S,9); 1.37, 1.58 and 1.97 (M,5); 3.21 (M,2). IR 11.63μ. Anal. Calculated for $C_9H_{16}O$: C, 77.09%; H, 11.50%. Found: C, 76.70%; H, 11.50%. Mass Spectra 140 (0.006), 107 (0.13), 84 (0.30), 83 (base peak), 67 (0.20), 57 (0.67), 56 (0.17), 55 (0.57), 41 (0.64), 37.4 (metastable ion).

trans-3-t-Butylcyclopentene oxide, b.p. 64°/12 mm., NMR 0.93 (S,9); 1.47, 1.75 and 1.91 (M,5); 3.29 (M,2). IR 11.94μ. Anal. Calculated for $C_9H_{16}O$: C, 77.09%; H, 11.50%. Found: C, 76.89%; H, 11.53%. Mass Spectra 140 (0.002), 107 (0.06), 84 (0.23), 83 (base peak), 67 (0.06), 57 (0.52), 56 (0.07), 55 (0.47), 41 (0.33), 37.4 (metastable ion).

The epoxidation of 3-t-butylcyclopentene with m-chloroperbenzoic acid was also carried out in cyclohexane and absolute ethanol using the above procedure. The ratios of trans- to cis-epoxide were 82/18 and 90/10 respectively. The reaction in ethanol was not a clean reaction with other products being formed.

3-Isopropylcyclopentene (prepared in the same manner as the corresponding t-butyl compound) gave a cis- to trans-epoxide ratio of 58/42 upon oxidation with m-chloroperbenzoic acid. The corresponding IR peaks were at 11.69 and 11.94μ.

With monoperoxyphthalic acid 3-t-Butylcyclopentene, (1.06 gms., 0.0086 mole) purified by spinning band distillation, was added to 0.014 mole of an ethereal solution of monoperoxyphthalic acid. After stirring for 24 hours, the solution was extracted three times with a saturated sodium bicarbonate solution. The organic layer was then dried over anhydrous magnesium sulfate, and most of the ether was removed on a steam bath.

GPC on a 10 foot Ucon LB 550X column at 145° indicated the ratio of trans-3-t-butylcyclopentene oxide to cis-3-t-butylcyclopentene oxide was 78:22 and the reaction had gone 70% to completion based on unreacted olefin.

With trifluoroperacetic acid The trifluoroperacetic acid was added slowly to a mixture of 12.7 gms. (0.12 mole) of sodium carbonate and 3 gms. (0.024 mole) of 3-t-butylcyclopentene in 25 mls. of methylene chloride. After stirring for three hours, the insoluble salts were filtered and triturated with 30 mls. of methylene chloride. The combined methylene chloride solutions were extracted with sodium bicarbonate, and the aqueous layer was extracted once with pentane. The combined pentane-methylene chloride solutions were dried over magnesium sulfate and most of the solvent was removed on a steam bath.

GPC indicated the epoxidation had gone 97% to completion (based on unreacted olefin) and the ratio of trans-3-t-butylcyclopentene oxide to the cis-isomer was 83:17.

With peracetic acid One gram of 3-t-butylcyclopentene (0.008 mole) dissolved in 15 mls. of methylene chloride was slowly added to a

mixture of 0.1 gm. of sodium acetate in six mls. (0.027 mole) of 42% peracetic acid (FMC Corp. analysis indicated 5.06% of hydrogen peroxide was present). After reacting for five hours, an equal volume of water was added. The aqueous layer was extracted twice with pentane. The combined organic layers were extracted with a saturated sodium bicarbonate solution and then dried over magnesium sulfate. Most of the solvent was removed on a steam bath prior to chromatography.

GPC indicated the reaction had gone 95% to completion based on unreacted starting material and the ratio of trans-3-t-butylcyclopentene oxide to the cis-epoxide was 83:17.

The epoxidation was also run using the above procedure with diethyl ether as the solvent. GPC of the reaction mixture after two hours indicated 71% completion with a trans- to cis-epoxide ratio of 79:21.

Reduction

Epoxides with hydrogen and catalyst trans-3-t-Butylcyclopentene oxide (10.55 gms., 0.075 mole, GPC indicates 99.9% of trans-isomer) in 350 mls. of absolute ethanol was hydrogenated using three porcelain scoopfuls of W-2 Raney nickel (142) (stored under absolute ethanol for six months). This was allowed to react for 5 days under a slight hydrogen pressure (15-30 mm. of mercury). Approximately one gram of Celite was added to trap the finely divided catalyst and the solution was vacuum filtered through a sintered glass funnel. After most of the ethanol was evaporated on a steam bath, the solution was distilled using an 18 in. (6 mm.) Nester/Faust spinning band column to separate the trans-2- and 3-t-butylcyclopentanols.

GPC of the mixture prior to distillation on a ten foot Ucon LB 550X column at 150° indicated reduction was 88% complete based on the starting epoxides, and the ratio of trans-3-t-butylcyclopentanol to trans-2-t-butylcyclopentanol was 81:19. GPC of the 2-t-butylcyclopentanol on a four foot LAC 446 column at 130° indicated no cis-alcohol was present.

trans-3-t-Butylcyclopentanol, b.p. 75-76°/5 mm., m.p. 19-20°, NMR 0.86 (S,9), 1.57 (M,7), 3.57 (S broad, 1), 4.19 (M,1). IR (μ) 3.00, 6.78, 9.95, 10.17.

Attempted reduction of trans-3-t-butylcyclopentene oxide in absolute ethanol at 26°/10-25 mm. pressure using Adams catalyst (platinum oxide) (143) resulted only in isolation of starting material.

cis-3-t-Butylcyclopentene oxide (4.5 gms., 0.032 mole, GPC indicates 99% of cis-isomer) was reacted with four porcelain scoops of Raney nickel at 39° (refluxing methylene chloride) for five days under a slight positive pressure of hydrogen. After the reaction was worked up in the same manner as above, GPC indicated the reaction had gone 57% to completion.

Complete hydrogenation (99% from GPC based on starting epoxide) was accomplished using a Parr series 4500 pressure reaction apparatus. Four gms. of cis-3-t-butylcyclopentene oxide (0.029 mole, GPC indicates 98% of cis-isomer) was hydrogenated in 200 mls. of absolute ethanol using three scoops of Raney nickel catalyst at room temperature for two weeks under a pressure of 180 lbs./in.^{2}. After the addition of Celite, the solution was filtered through a sintered glass funnel. Most of the ethanol was removed on a steam bath, and GPC of the crude mixture on a four foot LAC 446 column at 145° indicated the ratio of cis-3-t-butylcyclopentanol to

cis-2-t-butylcyclopentanol was 88:12. The cis-alcohols from three runs were combined and distilled through an 18 in. by 6 mm. Nester/Faust spinning band column to give four gms. of the cis-3-alcohol. GPC of the cis-2-alcohol fractions on the LAC column at 145° indicated less than 2% of the trans-2-t-butylcyclopentanol was present.

cis-3-t-Butylcyclopentanol, b.p. 75°/5 mm., NMR 0.88 (S,9), 1.55 and 1.89 (M,7), 3.38 (S,1), 4.13 (M,1). IR (μ) 3.00, 6.80, 10.10, peak at 9.95 is absent.

Epoxides with lithium aluminum hydride trans-3-t-Butylcyclopentene oxide (14.2 gms., 0.102 mole, GPC indicated less than 2% of cis-isomer) is slowly added at 0° to a solution of 1.3 gms. (0.037 mole) of lithium aluminum hydride in 100 mls. of purified tetrahydrofuran. The solution was subsequently refluxed for three days. Water was then slowly added to destroy the excess hydride, followed by an equal volume of 1:12 sulfuric acid to dissolve the lithium salts. The aqueous layer was extracted once with ether and the combined ether-tetrahydrofuran layers were dried over anhydrous magnesium sulfate. Most of the solvent was removed on a steam bath, and GPC of the residue on a ten foot Ucon LB 550X column at 150° indicated that trans-3-t-butylcyclopentene oxide reacted to give only trans-2-t-butylcyclopentanol. Distillation of the product gave the same alcohol obtained in the greater yield from hydroboration of 3-t-butylcyclopentene.

Reduction of 0.006 mole of trans-3-t-butylcyclopentene oxide in 50 mls. of redistilled hexane with four mls. of a 1.1 M. lithium aluminum hydride solution in ether also gave, after refluxing for one week, a 100%

conversion to trans-2-t-butylcyclopentanol.

cis-3-t-Butylcyclopentene oxide (29.4 gms., 0.21 mole, GPC indicates 3% of trans-isomer is present) was added slowly to 2.28 gms. (0.06 mole) of lithium aluminum hydride in 350 mls. of dried diethyl ether. The solution was refluxed for four days. This was then worked up in the same manner as the reduction products from the trans-epoxide. GPC of the products on a ten foot Ucon LB 550X column at 150° indicated that the reaction went 94% to completion based on starting epoxide and that the ratio of cis-2-t-butylcyclopentanol to cis-3-t-butylcyclopentanol was 82:18. Distillation on a 4 foot glass helices packed Todd column produced 15 gms. of pure cis-2-t-butylcyclopentanol.

cis-2-t-Butylcyclopentanol, b.p. 54°/2 mm., m.p. 33-34°, NMR 1.01 (S,9), 1.37 and 1.63 (M,7), 2.02 (S,1), 4.23 (M,1). IR (μ) 2.92, 6.78, 9.86.

The kinetic reduction of a mixture of cis- and trans-epoxides with lithium aluminum hydride was studied as a function of solvent. (See Table 7). Three mls. of a 1.1 M. lithium aluminum hydride solution in ether was added to a mixture containing 32.6% of cis-3-t-butylcyclopentene oxide and 67.4% of trans-3-t-butylcyclopentene oxide (0.90 gm., 0.0064 mole) in 50 mls. of solvent. The solvents studied were 100% ether, 50:50 ether-hexane, and 100% hexane. The solutions were refluxed for three days and were worked up in the usual manner. GPC, using a ten foot Ucon LB 550X column at 140°, gave the per cent reduction, per cent 2- and 3-alcohol formation, and per cent cis- and trans-epoxide remaining. From this data the relative rates of cis- to trans-epoxide reduction were

determined using the equation derived by Weissberger (144), $k_{cis}/k_{trans} = \log \frac{(cis)i}{(cis)f} / \log \frac{(trans)i}{(trans)f}$.

Ketones with lithium aluminum hydride The 2- and 3-t-butylcyclopentanones were reduced to give a mixture of cis- and trans-alcohols using lithium aluminum hydride in ether. The t-butylcyclopentanone (2.6 gms., 0.019 mole) was slowly added to a solution of 0.7 gm. (0.02 mole) of lithium aluminum hydride in 150 mls. of anhydrous ether. The reaction mixture was stirred for seven hours under a slight positive pressure of nitrogen. Ten mls. of water was cautiously added and the lithium salts were dissolved in 100 mls. of 10% hydrochloric acid. The aqueous layer was extracted twice with a total of 200 mls. of ether. The combined ether layers were dried over anhydrous magnesium sulfate and most of the ether was evaporated on a steam bath.

3-t-Butylcyclopentanone upon reduction gave a mixture of 55% cis-3-t-butylcyclopentanol and 45% trans-3-t-butylcyclopentanol, as was determined by GPC using a 100 meter Golay capillary column at 65° with a Silicon SE 30 liquid phase.

2-t-Butylcyclopentanone gave a mixture of 50% cis-2-t-butylcyclopentanol and 50% trans-2-t-butylcyclopentanol using a four foot LAC 446 column at 130°. Conversion of the alcohol mixture to the acetates followed by GPC and NMR indicated the cis- to trans-isomer ratio was 56:44.

Equilibration

3-t-Butylcyclopentanol In an effort to determine the relative thermodynamic stabilities of the cis- and trans-isomers, the alcohols

were equilibrated under Meerwein-Ponndorf-Oppenauer conditions using the procedure reported by DePuy and Story (145). 3-t-Butylcyclopentanol (0.6 gm., 0.004 mole, NMR indicated ratio of cis- to trans-alcohol is approximately 55:45) was added to 0.86 gm. (0.004 mole) of aluminum isopropoxide in 50 mls. of dry isopropyl alcohol. One ml. of reagent grade acetone was added and the mixture was refluxed for nine days. Hydrochloric acid (100 mls. of 10%) was then added and the aqueous layer was extracted three times with ether. The combined extracts were dried over anhydrous magnesium sulfate and most of the ether and isopropyl alcohol was evaporated on a Rotovac. GPC using a 100 meter Golay column indicated the ratio of cis-3-t-butylcyclopentanol to trans-3-t-butylcyclopentanol was 52:48.

2-t-Butylcyclopentanols The activity of the aluminum isopropoxide was measured by reducing cyclohexanone and the equilibration procedure was checked using a mixture of the two diastereoisomeric trans-2-decalols.

One gm. of 2-t-butylcyclopentanone was reduced with 1.4 gms. of aluminum isopropoxide in 100 mls. of isopropyl alcohol. The mixture was refluxed for 7 days, while slowly removing the acetone formed by distillation. Most of the isopropyl alcohol was then distilled over and the residue was taken up in ether. This solution was extracted with a 10% sulfuric acid solution and most of the ether was removed by distillation on a steam bath. GPC of the mixture using a 4 foot LAC 446 column at 125° indicated a 52% conversion to the 2-t-butylcyclopentanols---the ratio of cis- to trans-alcohol being 90:10. Using the above procedure,

cyclohexanol was formed in quantitative yield after 24 hrs. from cyclohexanone.

trans-2-t-Butylcyclopentanol was equilibrated in the same manner as the 3-isomer. After 11 days, GPC on a 4 foot LAC 446 column at 125° indicated no cis-2-alcohol was present and less than 1% of the 2-t-butylcyclopentanone was formed. Equilibration of cis-2-t-butylcyclopentanol for 11 days under the same conditions gave 40% of 2-t-butylcyclopentanone and a 78:22 mixture of cis- and trans-2-t-butylcyclopentanols.

The equilibration for a period of 8 months of a 50:50 mixture of the cis- and trans-2-t-butylcyclopentanols obtained from lithium aluminum hydride reduction of the corresponding ketone yielded a 53:47 mixture of trans- to cis-2-t-butylcyclopentanol.

Purification of materials

Ether Ether was distilled from lithium aluminum hydride prior to use.

Tetrahydrofuran Tetrahydrofuran was purified by distillation from potassium hydroxide pellets followed by distillation from lithium aluminum hydride. The solution was stored over molecular sieves (Linde Type 4A).

Ethanol Residual water was removed from absolute ethanol by the method of Manske (146) using a sodium and diethyl phthalate followed by distillation.

t-Butyl alcohol Commercial t-butyl alcohol (Eastman White Label) was distilled four times from freshly cut sodium (approximately 5 gms./liter of alcohol) into Pyrex flasks which had been washed with 10%

hydrofluoric acid, rinsed with distilled water and dried.

Potassium Lump potassium was melted in n-heptane. The molten potassium was stirred and the impurities which floated to the top were skimmed off with a spatula. This procedure was repeated until a very shiny metallic surface was formed.

Potassium t-butoxide Purified potassium was washed twice in purified t-butyl alcohol before transferring to the anhydrous t-butyl alcohol in a flask with a drying tube. The solution remained clear and colorless under anhydrous conditions for an indefinite period of time. Rate constants determined with solutions prepared by this method were consistent and reproducible.

Sodium ethoxide Freshly cut sodium was rinsed twice in anhydrous ethanol and then was transferred to a flask containing the purified ethanol equipped with a drying tube. The solution was stored under nitrogen prior to use.

Pyridine Commercial pyridine was distilled from barium oxide and was stored in a desiccator.

n-Pentane The pentane used in the recrystallizations of the p-toluenesulfonates was washed with equal portions (six to eight times) of concentrated sulfuric acid until the acid layer remained colorless. This was then washed once with water, dried over magnesium sulfate, and distilled.

Procedures and Data for Beta Elimination Reactions

Base catalyzed eliminations

Second order elimination reactions The desired compound (approx-

imately 0.0025 mole) was accurately weighed into a 50 ml. volumetric flask. Fifty mls. of 0.1 molar base, equilibrated at the reaction temperature, was added to the substrate and the mixture was shaken until solution was complete. The flask was then immersed in a constant temperature bath of the desired temperature. The temperature was measured to $\pm 0.02^{\circ}$ with a National Bureau of Standards calibrated thermometer.

The kinetics were measured by quenching a 5 ml. aliquot in 50 mls. of ice-water and immediately titrating the excess base with standard hydrochloric acid. The base was standardized by this procedure at each reaction temperature. Infinity points taken experimentally generally agreed with calculated values.

The rates were calculated from the integrated form of the second order rate equation by taking the average of the individual rates calculated from each experimental point.

$$k_2 = \frac{2.303}{(a-b)t} \log \frac{b(a-x)}{a(b-x)}$$

The rates were also calculated using the method of least squares by an IBM 7074 computer.

The hydrochloric acid was standardized as 0.1022 N. by titrating to the phenolphthalein pink end point with a 0.1009 N. sodium hydroxide solution, which was standardized using a weighed amount of potassium acid phthalate.

Kinetics employing higher base concentrations were determined using the above procedure, except withdrawing 2 ml. aliquots from a 25 ml. volumetric flask.

Tables 22 through 45 give the rates of the base-promoted second order elimination reactions. The time elapsed is in seconds, the volume of titrant is in mls. of standard hydrochloric acid, and the rate constant is in liter $mole^{-1}sec.^{-1}$. The initial concentrations of substrate and base, the computer rate, the average rate constant from two or more kinetic runs, the measured and calculated infinity points, and the relative percentages of the olefins formed are included in the tables.

Table 22. Cyclopentyl chloride, 49.64°, 0.1015 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b(a-x)}{a(b-x)}$	$k_2 \times 10^6$
0	4.96	---	----
420,594	4.69	0.02721	2.89
869,459	4.47	0.05278	2.71
1,436,183	4.25	0.08284	2.58
3,069,383	3.83	0.15843	2.36
Average rate[a]			2.64 ± 0.16

[a]Conc. of chloride = 0.0500 M., computer rate = 2.17 ± 0.04, J. Smith's (32) rate = 2.6 ± 0.1, calculated infinity point = 2.52.

Table 23. Cyclopentyl bromide, 49.64°, 0.1015 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a} \frac{(a-x)}{(b-x)}$	$k_2 \times 10^4$
0	4.74	---	----
3,649	4.59	0.01439	1.77
14,951	4.22	0.06251	1.88
25,067	3.98	0.10235	1.83
53,845	3.48	0.22308	1.86
80,716	3.20	0.33278	1.85
108,176	3.04	0.42321	1.76
Average rate[a]			1.82 ± 0.04

[a]Conc. of bromide = 0.0502 M., computer rate = 1.91 ± 0.02, J. Smith's (32) rate = 1.92 ± 0.04, infinity point: measured 2.56, calculated 2.50.

Table 24. Cyclopentyl bromide, 70.33°, 0.1091 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a} \frac{(a-x)}{(b-x)}$	$k_2 \times 10^3$
0	4.97	---	----
1,448	4.38	0.01924	1.22
2,716	3.98	0.03623	1.23
3,926	3.70	0.05085	1.19
5,128	3.44	0.06755	1.21
7,240	3.08	0.09558	1.21
10,948	2.66	0.14236	1.20
24,696	1.88	0.32697	1.22
Average rate[a]			1.21 ± 0.01

[a]Conc. of bromide = 0.0882 M., computer rate = 1.23 ± 0.003, infinity point: measured 1.21, calculated 1.02.

Table 25. Cyclopentyl bromide, 50.20°, 0.2908 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a}\frac{(a-x)}{(b-x)}$	$k_2 \times 10^4$
0	5.56	---	----
983	5.43	0.01488	2.09
2,272	5.28	0.03367	2.05
4,047	5.08	0.06195	2.12
6,193	4.89	0.09301	2.08
11,794	4.54	0.16501	1.98
15,848	4.30	0.23082	2.01
22,883	4.04	0.32729	1.98
35,110	3.74	0.50121	1.97
Average rate[a]			2.03 ± 0.05

[a]Conc. of bromide = 0.1251 M., computer rate = 1.97 ± 0.01, infinity point: calculated 3.24.

Table 26. Cyclopentyl bromide, 50.20°, 0.2821 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a}\frac{(a-x)}{(b-x)}$	$k_2 \times 10^4$
0	5.15	---	----
1,372	4.98	0.01085	2.30
2,815	4.84	0.03999	2.15
4,855	4.67	0.06608	2.06
8,446	4.40	0.11581	2.07
13,606	4.12	0.18265	2.03
20,822	3.86	0.26676	1.92
Average rate[a]			2.09 ± 0.07

[a]Conc. of bromide = 0.1298 M., computer rate = 1.93 ± 0.02, infinity point: calculated 2.98.

Table 27. Cyclopentyl p-toluenesulfonate, 49.64°, 0.1017 M. t-butoxide/ t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a}\frac{(a-x)}{(b-x)}$	$k_2 \times 10^4$
0	4.54	---	----
3,197	4.32	0.02781	3.88
6,746	4.13	0.05672	3.75
10,705	3.92	0.09476	3.95
14,629	3.76	0.12937	3.94
22,097	3.54	0.18800	3.81
40,358	3.14	0.35214	3.89
75,368	2.78	0.67667	4.00
Average rate[a]			3.89 ± 0.07

[a]Conc. of p-toluenesulfonate = 0.0501 M., computer rate = 4.01 ± 0.02, J. Smith's (32) rate = 3.86 ± 0.01, infinity point: measured 2.55, calculated 2.52.

Table 28. Cyclopentyl p-toluenesulfonate, 50.20°, 0.2908 M. t-butoxide/ t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a}\frac{(a-x)}{(b-x)}$	$k_2 \times 10^4$
0	5.54	---	----
1,841	5.34	0.07484	4.09
2,954	5.22	0.13024	4.43
4,394	5.14	0.17322	3.97
6,149	5.00	0.26477	4.33
8,116	4.92	0.33032	4.09
11,626	4.76	0.51225	4.43
15,280	4.68	0.65102	4.29
Average rate[a,b,c]			4.23 ± 0.16

[a]Conc. of p-toluenesulfonate = 0.0610 M., computer rate = 4.35 ± 0.05, infinity point: measured 4.48, calculated 4.49.

[b]Duplicate run with base conc. = 0.2995 gave $k_2 = 4.36 \pm 0.13 \times 10^{-4}$, computer rate = 4.54 ± 0.01.

[c]Duplicate run with base conc. = 0.2821 M. gave $k_2 = 4.37 \pm 0.16 \times 10^{-4}$, computer rate = 4.24 ± 0.06.

Table 29. 3-Phenylcyclopentyl p-toluenesulfonate, 50.22°, 0.1108 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a} \frac{(a-x)}{(b-x)}$	$k_2 \times 10^4$
0	5.29	---	----
9,097	4.86	0.08098	2.88
16,849	4.68	0.12529	2.41
28,845	4.36	0.22923	2.57
42,808	4.12	0.34294	2.59
79,365	3.78	0.63459	2.59
Average rate[a]			2.61 ± 0.11

[a]Conc. of p-toluenesulfonate = 0.0397 M., computer rate = 2.59 ± 0.02, infinity point: calculated 3.48; product ratio: % 4-olefin/% 3-olefin = 69/31.

Table 30. 3-Phenylcyclopentyl p-toluenesulfonate, 70.33°, 0.1096 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a} \frac{(a-x)}{(b-x)}$	$k_2 \times 10^3$
0	5.17	---	----
905	4.96	0.04894	1.64
2,247	4.68	0.13285	1.80
3,923	4.49	0.20845	1.66
6,266	4.28	0.32184	1.56
10,093	4.05	0.51722	1.56
15,087	3.87	0.81109	1.64
Average rate[a]			1.64 ± 0.06

[a]Conc. of p-toluenesulfonate = 0.0337 M., computer rate = 1.61 ± 0.02, infinity point: measured 3.70, calculated 3.47; product ratio: % 4-olefin/% 3-olefin = 69/31.

Table 31. 3-Phenylcyclopentyl p-toluenesulfonate, 50.03°, 0.2780 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a}\frac{(a-x)}{(b-x)}$	$k_2 \times 10^4$
0	5.26	---	----
1,274	5.19	0.04366	3.35
2,998	5.10	0.10929	3.56
4,403	5.04	0.16088	3.57
5,866	5.00	0.19983	3.30
7,745	4.95	0.25505	3.22
10,557	4.88	0.34898	3.23
14,379	4.80	0.49441	3.37
29,969	4.66	1.06134	3.46
Average rate[a]			3.39 ± 0.11

[a]Conc. of p-toluenesulfonate = 0.0431 M., computer rate = 3.45 ± 0.03, infinity point: calculated 4.61; product ratio: % 4-olefin/% 3-olefin = 71/29.

Table 32. trans-3-t-Butylcyclopentyl p-toluenesulfonate, 50.08°, 0.1194 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a}\frac{(a-x)}{(b-x)}$	$k_2 \times 10^4$
0	5.67	---	----
5,329	5.46	0.03391	1.90
8,774	5.35	0.05395	1.85
12,905	5.18	0.08871	2.07
17,881	5.06	0.11660	1.96
29,439	4.80	0.18977	1.94
59,258	4.32	0.40933	2.02
Average rate[a,b]			1.96 ± 0.07

[a]Conc. of p-toluenesulfonate = 0.0431 M., computer rate = 2.09 ± 0.02, infinity point: calculated 3.75, experimental 3.82; product ratio: % 4-olefin/% 3-olefin = 88/12.

[b]Duplicate run with base conc. = 0.1090 M. gave k_2 = 1.95 ± 0.13, computer rate = 1.97 ± 0.04.

Table 33. trans-3-t-Butylcyclopentyl p-toluenesulfonate, 70.20°, 0.1147 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a}\frac{(a-x)}{(b-x)}$	$k_2 \times 10^3$
0	5.37	---	----
1,458	5.07	0.05671	1.30
2,539	4.90	0.09606	1.26
3,775	4.72	0.14562	1.29
5,410	4.50	0.22180	1.37
7,708	4.30	0.31403	1.36
12,603	4.06	0.47815	1.27
Average rate[a]			1.31 ± 0.04

[a]Conc. of p-toluenesulfonate = 0.0409 M., computer rate = 1.19 ± 0.02, infinity point: calculated 3.62.

Table 34. cis-3-t-Butylcyclopentyl p-toluenesulfonate, 50.20°, 0.1089 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a}\frac{(a-x)}{(b-x)}$	$k_2 \times 10^4$
0	5.06	---	----
1,288	4.98	0.01364	3.58
3,025	4.88	0.03198	3.58
6,781	4.67	0.07611	3.80
12,402	4.45	0.13303	3.63
19,585	4.24	0.20222	3.49
31,172	3.98	0.32086	3.48
46,885	3.75	0.48467	3.50
Average rate[a,b]			3.58 ± 0.08

[a]Conc. of p-toluenesulfonate = 0.0400 M., computer rate = 3.47 ± 0.02, infinity point: measured 3.33, calculated 3.37; product ratio: % 4-olefin/% 3-olefin = 78/22.

[b]Duplicate run with base conc. = 0.1081 M. gave $k_2 = 3.50 \pm 0.06$, computer rate = 3.45 ± 0.03.

Table 35. 3-t-Butylcyclopentyl bromide, 50.22°, 0.1106 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a}\frac{(a-x)}{(b-x)}$	$k_2 \times 10^5$
0	5.22	---	----
6,869	5.05	0.01365	9.04
14,662	4.84	0.03253	10.00
25,585	4.64	0.05301	9.34
45,816	4.25	0.10225	10.06
86,573	3.79	0.18495	9.63
138,199	3.38	0.30134	9.83
Average rate[a]			9.65 ± 0.31

[a]Conc. of bromide = 0.0680 M., computer rate = 9.82 ± 0.07, infinity point: measured 2.50, calculated 2.10; product ratio: % 4-olefin/% 3-olefin = 86/14.

Table 36. 3-t-Butylcyclopentyl bromide, 70.33°, 0.1091 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a}\frac{(a-x)}{(b-x)}$	$k_2 \times 10^4$
0	5.20	---	----
1,826	4.98	0.03719	6.79
3,622	4.83	0.06666	6.13
6,316	4.62	0.11528	6.08
9,943	4.40	0.17891	6.00
14,446	4.16	0.27107	6.25
22,039	3.88	0.43393	6.56
Average rate[a]			6.30 ± 0.25

[a]Conc. of bromide = 0.0482 M., computer rate = 6.56 ± 0.09, infinity point: measured 3.38, calculated 2.99; product ratio: % 4-olefin/% 3-olefin = 87/13.

Table 37. 3-t-Butylcyclopentyl bromide, 50.03°, 0.2780 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a} \frac{(a-x)}{(b-x)}$	$k_2 \times 10^4$
0	5.26	---	----
2,067	5.20	0.02245	1.15
7,372	5.08	0.07301	1.04
14,584	4.93	0.15018	1.08
19,861	4.89	0.17522	0.93
27,670	4.77	0.25856	0.96
41,354	4.62	0.40340	1.03
Average rate[a]			1.03 ± 0.06

[a]Conc. of bromide = 0.0666 M., computer rate = 1.01 ± 0.02, infinity point: measured 4.28, calculated 4.14; product ratio: % 4-olefin/% 3-olefin = 86/14.

Table 38. trans-2-t-Butylcyclopentyl p-toluenesulfonate, 50.22°, 0.1102 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a} \frac{(a-x)}{(b-x)}$	$k_2 \times 10^4$
0	5.28	---	----
17,993	5.02	0.06455	1.05
29,532	4.87	0.11042	1.10
47,161	4.66	0.19031	1.18
62,568	4.39	0.34762	1.24
116,650	4.22	0.48126	1.21
Average rate[a,b]			1.16 ± 0.06

[a]Conc. of p-toluenesulfonate = 0.0331 M., computer rate = 1.27 ± 0.09, infinity point: measured 3.84, calculated 3.77.

[b]Duplicate run with base conc. = 0.1003 M. and temperature = 50.43° gave $k_2 = 1.17 \pm 0.04$, computer rate = 1.33 ± 0.03.

Table 39. trans-2-t-Butylcyclopentyl p-toluenesulfonate, 70.33°, 0.1094 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a} \frac{(a-x)}{(b-x)}$	$k_2 \times 10^4$
0	5.18	---	----
5,402	4.60	0.17228	9.61
8,922	4.38	0.27932	9.43
12,527	4.24	0.37243	8.96
18,161	4.05	0.56010	9.29
25,957	3.87	0.91769	10.65
Average rate[a]			9.59 ± 0.38

[a]Conc. of p-toluenesulfonate = 0.03278 M., computer rate = 10.38 ± 0.19, infinity point: calculated 3.74; product ratio: % 1-olefin/% 3-olefin = 65/35.

Table 40. trans-2-t-Butylcyclopentyl p-toluenesulfonate, 50.03°, 0.2739 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a} \frac{(a-x)}{(b-x)}$	$k_2 \times 10^4$
0	5.26	---	----
3,023	5.20	0.03336	1.09
6,886	5.12	0.08367	1.20
12,452	5.06	0.12685	1.01
17,612	5.00	0.17603	0.99
25,031	4.92	0.25404	1.01
34,240	4.83	0.36706	1.06
47,386	4.75	0.50593	1.06
78,300	4.62	0.94981	1.20
Average rate[a,b,c]			1.08 ± 0.06

[a]Conc. of p-toluenesulfonate = 0.0472 M., computer rate = 1.19 ± 0.03, infinity point: measured 4.55, calculated 4.51; product ratio: % 1-olefin/% 3-olefin = 32/68.

[b]Duplicate run with base conc. = 0.2949 M. gave k_2 = 1.07 ± 0.13, computer rate = 0.88 ± 0.03, product ratio: % 1-olefin/% 3-olefin = 30/70.

[c]Duplicate run with base conc. = 0.2909 M. gave k_2 = 0.96 ± 0.05, computer rate = 1.00 ± 0.02.

Table 41. cis-2-t-Butylcyclopentyl p-toluenesulfonate, 50.20°, 0.1083 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a}\frac{(a-x)}{(b-x)}$	$k_2 \times 10^3$
0	5.20	---	----
1,375	5.02	0.08161	1.56
3,063	4.85	0.18362	1.57
5,083	4.72	0.28893	1.49
7,265	4.60	0.42388	1.53
10,187	4.50	0.59042	1.52
16,738	4.37	1.03362	1.62
Average rate[a,b]			1.55 ± 0.04

[a]Conc. of p-toluenesulfonate = 0.0214 M., computer rate = 1.61 ± 0.02, infinity point: measured 4.30, calculated 4.26; product ratio: % 1-olefin/% 3-olefin = 92/08.

[b]Duplicate run with base conc. = 0.1104 M. gave k_2 = 1.62 ± 0.07, computer rate = 1.66 ± 0.02, product ratio: % 1-olefin/% 3-olefin = 94/06.

Table 42. cis-2-t-Butylcyclopentyl p-toluenesulfonate, 30.18°, 0.1104 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a}\frac{(a-x)}{(b-x)}$	$k_2 \times 10^4$
0	5.26	---	----
3,489	5.17	0.02727	2.15
8,771	5.08	0.05742	1.80
22,636	4.84	0.15699	1.91
31,029	4.72	0.22180	1.97
40,062	4.60	0.30239	2.08
50,492	4.54	0.35105	1.92
Average rate[a]			1.97 ± 0.10

[a]Conc. of p-toluenesulfonate = 0.02878 M., computer rate = 1.98 ± 0.04, infinity point: measured 4.09, calculated 3.99.

Table 43. cis-2-t-Butylcyclopentyl p-toluenesulfonate, 50.03°, 0.2729 M. t-butoxide/t-butyl alcohol.

Time elapsed	Volume of titrant	$\log \frac{b}{a}\frac{(a-x)}{(b-x)}$	$k_2 \times 10^4$
0	5.30	---	----
1,869	4.94	0.12198	6.87
3,000	4.83	0.19138	6.72
6,513	4.57	0.44531	7.20
9,167	4.48	0.59804	6.87
12,884	4.40	0.81206	6.64
Average rate[a,b]			6.86 ± 0.15

[a]Conc. of p-toluenesulfonate = 0.0284 M., computer rate = 6.71 ± 0.15, infinity point: measured 4.28, calculated 4.23; product ratio: % 1-olefin/% 3-olefin = 85/15.

[b]Duplicate run with base conc. = 0.2909 M. at 50.20° gave k_2 = 6.90 ± 0.32, computer rate = 7.04 ± 0.14, product ratio: % 1-olefin/% 3-olefin = 83/17.

Table 44. trans-2-Phenylcyclopentyl bromide, 50.00°, 0.1003 M. t-butoxide/t-butyl alcohol.[a,b]

Time elapsed	Volume of titrant	$\log \frac{b}{a}\frac{(a-x)}{(b-x)}$
0	4.64	---
6,655	4.54	0.00985
22,496	4.34	0.03167
48,470	4.10	0.06248
93,886	3.83	0.10521
182,335	3.48	0.17989
285,648	3.17	0.27719
Graphical rate[c,d]		4.28×10^{-5}

[a]Starting compound was a 77:23 mixture of trans- to cis-isomers. Compounds were allowed to react for 15 minutes prior to zero point.

[b]Computer rate = 4.50 ± 0.08 x 10^{-5}, conc. of bromide = 0.0511 M., infinity point = 2.34, product ratio: % 1-olefin/% 3-olefin = 69/31.

[c]Slope of straight line drawn through the last 5 points obtained by plotting log b (a-x)/a (b-x) vs. time

[d]Duplicate run at 50.22° and 0.112 M. base gave k_2 (graphical) = 4.41 x 10^{-5}, product ratio: % 1-olefin/% 3-olefin = 63/37.

Table 45. cis- and trans-2-Phenylcyclopentyl bromide, 30.18°, 0.1124 M. t-butoxide/t-butyl alcohol.[a]

Time elapsed	Volume of titrant	$\log \frac{b\ (a-x)}{a\ (b-x)}$
0	5.31	---
173	5.22	0.01524
413	5.14	0.02972
751	5.08	0.04122
2,045	5.06	0.04519
150,425	4.78	0.10889
298,924	4.61	0.15720
573,240	4.42	0.22382
Graphical rate of cis-isomer[b]		2.75×10^{-2}
Graphical rate of trans-isomer[c]		7.62×10^{-6}

[a]Starting compound was a 77:23 mixture of trans- to cis-isomers, conc. of bromide = 0.0401 M., infinity point: measured 3.54, calculated 3.54.

[b]Graphing data in table and extrapolating the trans rate to zero time gives an infinity point of 5.07 for the cis-isomer. The slope of the line and the average of the rates calculated from each experimental point agreed, computer rate = $2.99 \pm 0.01 \times 10^{-2}$.

[c]Obtained using 5.06 as the initial point, computer rate = $8.53 \pm 0.31 \times 10^{-6}$.

Solvolysis check in second order eliminations The procedure of Siggia (125) was used to determine the per cent cyclopentene formed in the elimination of cyclopentyl bromide and cyclopentyl p-toluenesulfonate. The substrate was eliminated at 50° in 50 mls. of 0.1019 M. t-butoxide/t-butyl alcohol solution for 6 days. The sample was then transferred after cooling into a 125 ml. flask using 15 mls. of carbon tetrachloride. The excess potassium t-butoxide was titrated to the phenolphtalein end point with 1.0 M. hydrochloric acid and an excess of 3 drops

was added. Cyclopentene, containing an equimolar amount of p-toluenesulfonic acid, was processed in an identical manner.

A calculated excess (10-15%) of 0.1 N. bromate-bromide solution (29 mls.) was introduced into a 250 ml. hydrogenation flask, which was completely wrapped in aluminum foil and fitted with a 125 ml. addition funnel. The flask was evacuated with a water aspirator and 6 mls. of 6 N. sulfuric acid added (3 minutes being allowed for complete bromine evolution). Then 21 mls. of 0.2 N. mercuric sulfate was added, followed by the sample to be analyzed (0.0025 M. in unsaturation). The transfer flask was washed twice with a total of 30 mls. of carbon tetrachloride and 20 mls. of glacial acetic acid was added. Complete bromination had occurred after 10 minutes of shaking. Then 19 mls. of 2 N. sodium chloride was added followed by 19 mls. of 20% potassium iodide solution. The vacuum was broken and the solution was transferred to a 500 ml. Erlenmeyer flask with 15 mls. of carbon tetrachloride. The solution was then titrated with 0.05 N. sodium thiosulfate until the reddish-brown color changed to a deep yellow. Five mls. of ether was then added followed by a few mls. of a 1% starch solution. The black-brown color is then titrated to a colorless end point. A blank containing 10 mls. of the bromate-bromide solution was run under the same conditions as above. The quantitative bromination results are given in Table 46.

Gas phase chromatography and nuclear magnetic resonance indicated the only product formed from elimination of the cyclopentyl compounds was cyclopentene.

Determination of olefin ratios The determination of the product olefin ratio versus the base concentration was studied at 50°. A weighed

Table 46. Quantative brominations of cyclopentene formed from the second order elimination of the bromide and p-toluenesulfonate.

Compound	Mls. of thiosulfate[b]	Moles of olefin	Per cent recovery
Blank	52.2	---	
Cyclopentene	3.1	0.00239	96
Cyclopentyl bromide	2.3	0.00244	97
Cyclopentyl p-toluenesulfonate	5.6	0.00227	91[c]

[a]Starting concentrations were 0.0025 M.

[b]Standardized as 0.0487 M. using potassium iodate.

[c]Duplicate run using a sealed tube gave 89% recovery.

amount of substrate (0.1 gm.) in 10 mls. of base was reacted from three to seven days. The solution was then poured into water and 100 mls. ether was added. The ethereal layer was extracted four times with an equal volume of water and then dried over magnesium sulfate. Most of the ether was distilled on a steam bath and the olefin ratio was then analyzed by GPC. In the kinetic runs the olefin ratio at the infinity point was measured using the above procedure.

The t-butyl olefins were analyzed at 100° on a 25 ft. column containing 5% bis (ethyl hexyl) tetrachlorophthalate on 80-100 mesh Chromosorb W (HMDS treated). A 25 ft. column of Zonel E-7 (10%) on 60-80 mesh Chromosorb W (HMDS treated) at 110° was used for separation of the phenyl olefins. Separation of 1-phenylcyclopentene from 3-phenylcyclopentene was accomplished using a 10 ft. Ucon LB 550X column at 200°.

Pseudo first order elimination reactions The rates of elimination of 2-phenylcyclopentyl bromide, isomerization of 3-phenylcyclopentene, and elimination of 2-phenylethyl p-toluenesulfonate were followed with a Beckman DU DK-2A Recording Spectrophotometer. A solution 0.005 molar in the desired compound and 0.1 or 0.3 molar in base was prepared by adding the base, equilibrated at the reaction temperature, to an accurately weighed sample of the substrate in a 50 ml. volumetric flask. The mixture was shaken until solution was complete and then immersed into a constant temperature bath. Five ml. aliquots were withdrawn at appropriate intervals and quenched by draining into cold 95% ethanol. These solutions were allowed to warm to room temperature and were then diluted to the proper concentrations---a total of 100:1. The cyclopentene concentration was measured by ultraviolet spectroscopy at 256.5 mμ.

All rates were pseudo first order and were calculated from a modified integrated form of the first order rate equation.

$$k_1 = \frac{2.303}{t} \log \frac{a}{a-x} = \frac{2.303}{} \log \frac{A_\infty - A_0}{A_\infty - A_t}$$

Rates were calculated by taking the average of the indivdual rates calculated from each point and these were compared with the calculated rates, using the method of least squares, by an IBM 7074 computer. Second order rates were obtained by dividing the first order rate constant by the base concentration.

The rates of elimination from cis- and trans-2-phenylcyclopentyl bromide were determined from a 23:77 mixture of the isomers using the method of Siggia and Hanna (128) (graphically extrapolating to calculate the infinity point of the cis-isomer). The rate constant was calculated

from the slope of the line formed by plotting log $\frac{A_\infty - A_0}{A_\infty - A_t}$ vs. time.

The 77:23 mixture of trans- to cis-2-phenylcyclopentyl bromide was eliminated at 30° for 25 minutes in 0.1124 N. t-butoxide/t-butyl alcohol. The solution was quenched in water and the excess base was neutralized with 1.0 N. hydrochloric acid. Fifty mls. of carbon tetrachloride was added and this was extracted three times with a total of 150 mls. water. The carbon tetrachloride layer was dried over magnesium sulfate and most of the solvent was removed on a rotovac. An NMR of the filtered residue indicated the ratio of trans- to cis-bromide was 90:10 with 1-phenylcyclopentene as the only product.

Tables 47 through 56 give the rates of the base-promoted pseudo first order elimination reactions. The time elapsed is in seconds and the rate constant (k_1) is in sec^{-1}. The calculated second order rate constant, initial concentrations of base and substrate, the computer rate, the average rate constant from two or more kinetic runs, and the relative percentages of olefins formed are included in the tables.

Table 47. 2-Phenylethyl p-toluenesulfonate, 29.96°, 0.1085 M. t-butoxide/t-butyl alcohol.

Time elapsed	Absorbance[a]	log $\frac{A_\infty - A_0}{A_\infty - A_t}$	$k_1 \times 10^4$
0	0.233	---	----
604	0.358	0.06360	2.42
1,265	0.484	0.13275	2.42
2,360	0.648	0.24325	2.37
3,602	0.785	0.36361	2.27
4,975	0.904	0.50471	2.34
6,626	0.997	0.65961	2.29
Average rate[a]			2.35 ± 0.05

[a] $k_2 = 2.16 \times 10^{-3}$, J. Smith's rate (32) = 1.90×10^{-3}, conc. of p-toluenesulfonate = 0.0083 M., computer rate = $2.82 \pm 0.01 \times 10^{-4}$, infinity point: measured 1.214. ϵ = 13,800 at 248 mμ (32).

Table 48. Isomerization of 3-phenylcyclopentene to 1-phenylcyclopentene, 70.33°, 0.2927 M. t-butoxide/t-butyl alcohol.

Time elapsed	Absorbance[a]	$\log \frac{A_\infty - A_o}{A_\infty - A_t}$	$k_1 \times 10^4$
0	0.117	---	----
52,970	0.288	0.03277	1.43
76,450	0.375	0.05044	1.52
100,003	0.460	0.06842	1.58
155,233	0.641	0.13383	1.62
511,800	1.350	0.32240	1.45
848,820	1.867	0.59130	1.60
1,212,780	2.187	0.91983	1.75
Average rate[b]			1.56 ± 0.08

[a]3-Olefin: ε = 450 at 256.5 mμ, 1-olefin: ε = 14,710 at 256.5 mμ (32).

[b]$k_2 = 5.34 \times 10^{-6}$, conc. of 3-olefin = 0.0167 M., computer rate = 1.71 ± 0.41, infinity point: calculated 2.470.

Table 49. trans-2-Phenylcyclopentyl bromide, 50.22°, 0.1112 M. t-butoxide/t-butyl alcohol[a].

Time elapsed	Absorbance	$\log \frac{A_\infty - A_o}{A_\infty - A_t}$	$k_1 \times 10^6$
0	0.163	---	----
5,290	0.174	0.00700	3.05
17,176	0.198	0.02268	3.04
29,616	0.222	0.03894	3.03
45,069	0.265	0.06969	3.56
78,438	0.315	0.10843	3.18
123,087	0.391	0.17483	3.25
173,870	0.468	0.25439	3.36
Average rate[b,c]			3.21 ± 0.15

[a]Starting compound was a 77:23 mixture of trans- to cis-isomers. Compounds were allowed to react for 30 minutes prior to zero point.

[b]Graphical rate = 3.25, computer rate = 3.36 ± 0.04, $k_2 = 2.92 \times 10^{-5}$, conc. of bromide = 9.35×10^{-3} M., infinity point: measured 0.851/calculated 1.378 = 0.618.

[c]Duplicate run at 50.00° and 0.1000 M. base gave k_2 (graphical) = 2.78×10^{-5}, computer rate (k_1) = 2.92 ± 0.051 $\times 10^{-6}$.

Table 50. trans-2-Phenylcyclopentyl bromide, 29.96°, 0.1011 M. t-butoxide/t-butyl alcohol[a].

Time elapsed	Absorbance	$\log \frac{A_\infty - A_o}{A_\infty - A_t}$
0	0.107	---
80,947	0.163	0.03394
169,785	0.185	0.04803
260,506	0.216	0.06870
346,652	0.236	0.08258
448,652	0.256	0.09691
594,578	0.295	0.12630
Graphical rate[b,c]		$k_1 = 4.06 \times 10^{-7}$

[a]Starting compound was a 77:23 mixture of trans- to cis-isomers.

[b]Computer rate = $4.07 \pm 0.05 \times 10^{-7}$, k_2 (graphical) = 4.02×10^{-6}, conc. of bromide = 8.23×10^{-3} M., infinity point: experimental 0.852/calculated 1.21 = 0.705.

[c]Duplicate run at 30.18° and 0.1124 M. base gave k_1 (graphical) = 4.21×10^{-7}, computer rate = 4.05 ± 0.04, k_2 (graphical) = 3.75×10^{-6}.

Table 51. trans-2-Phenylcyclopentyl bromide, 70.33°, 0.1094 M. t-butoxide/t-butyl alcohol[a].

Time elapsed	Absorbance	$\log \frac{A_\infty - A_o}{A_\infty - A_t}$	$k_1 \times 10^5$
0	0.174	---	----
7,200	0.274	0.06296	2.01
15,782	0.389	0.14883	2.12
26,624	0.491	0.24245	2.10
42,220	0.606	0.37986	2.07
76,121	0.756	0.66842	2.02
103,958	0.828	0.93030	2.06
164,794	0.889	1.45485	2.03
Average rate[b]			2.06 ± 0.03

[a]Bromide mixture was allowed to react for 20 min. prior to zero point.

[b]Graphical rate = 2.03×10^{-5}, computer rate = $2.03 \pm 0.01 \times 10^{-5}$, k_2 (graphical) = 1.86×10^{-4}, conc. of bromide = 9.03×10^{-3} M., infinity point: measured 0.915/calculated 1.33 = 0.688.

[c]Duplicate run at 70.20° and 0.1011 M. base gave k_1 (graphical) = 2.09×10^{-5}, computer rate = $2.09 \pm 0.03 \times 10^{-5}$, $k_2 = 2.06 \times 10^{-4}$.

Table 52. trans-2-Phenylcyclopentyl bromide, 70.33°, 0.2927 M. t-butoxide/t-butyl alcohol[a].

Time elapsed	Absorbance	$\log \frac{A_\infty - A_o}{A_\infty - A_t}$	$k_1 \times 10^5$
0	0.184	---	----
2,294	0.273	0.05764	5.79
7,025	0.430	0.18281	5.99
12,122	0.564	0.32857	6.24
19,455	0.680	0.51249	6.07
30,682	0.792	0.82149	6.16
Average rate[b]			6.05 ± 0.13

[a]Bromide mixture was allowed to react for 10 min. prior to zero point.

[b]Graphical rate = 6.14×10^{-5}, computer rate = $6.18 \pm 0.03 \times 10^{-5}$, k_2 (graphical) = 2.10×10^{-4}, conc. of bromide = 8.84×10^{-3} M., infinity point: measured 0.900/calculated 1.30 = 0.692.

Table 53. cis-2-Phenylcyclopentyl bromide, 30.18°, 0.1124 M. t-butoxide/t-butyl alcohol[a].

Time elapsed	Absorbance	$\log \frac{A_\infty - A_o}{A_\infty - A_t}$	$k_1 \times 10^3$
0	0.134	---	----
352	0.212	0.36173	2.37
585	0.244	0.69272	2.73
835	0.255	0.90943	2.51
1,088	0.265	1.29478	2.74
1,290	0.268	1.53782	2.75
1,586	0.270	1.83885	2.69
Average rate[b,c]			2.63 ± 0.13

[a]Starting compound was a 23:77 mixture of cis- to trans-isomers. Infinity point (0.272) was determined by graphical extrapolation of the trans rate to zero time.

[b]Graphical rate = 2.72×10^{-3}, computer rate = 2.77 ± 0.04, k_2 (graphical) = 2.42×10^{-2}, conc. of bromide = 8.71×10^{-3} M.

[c]Duplicate run at 29.96° and 0.1011 M. base gave k_2 (graphical) = 2.40×10^{-2}, computer rate (k_1) = $2.35 \pm 0.07 \times 10^{-3}$.

Table 54. cis-2-Phenylcyclopentyl bromide, 30.18°, 0.2698 M. sodium ethoxide/ethanol[a].

Time elapsed	Absorbance	$\log \frac{A_\infty - A_0}{A_\infty - A_t}$	$k_1 \times 10^3$
0	0.102	---	----
178	0.142	0.13684	1.77
460	0.186	0.36408	1.82
7 739	0.208	0.54701	1.71
1,195	0.230	0.86923	1.68
1,695	0.240	1.17026	1.59
Average rate[b]			1.71 ± 0.07

[a]Starting compound was a 23:77 mixture of cis- to trans-isomers. Infinity point (2.50) was determined by graphical extrapolation of the trans rate to zero time.

[b]Graphical rate = 1.60×10^{-3}, computer rate = 1.56 ± 0.02, k_2 (graphical) = 5.94×10^{-3}, conc. of bromide = 7.85×10^{-3} M.

Table 55. trans-2-Phenylcyclopentyl bromide, 30.18°, 0.2698 M. sodium ethoxide/ethanol.

Time elapsed	Absorbance	$\log \frac{A_\infty - A_0}{A_\infty - A_t}$
0	0.102	---
5,078	0.250	0.06545
105,429	0.255	0.06784
236,783	0.261	0.07073
509,768	0.266	0.07315
711,914	0.268	0.07413
942,772	0.270	0.07510
Graphical rate[a]		1.69×10^{-8}

[a]Computer rate = 1.88 ± 0.17, k_2 (graphical) = 6.26×10^{-8}, conc. of bromide mixture = 7.852×10^{-3} M., infinity point: calculated 1.160.

Table 56. trans-2-Phenylcyclopentyl bromide, 70.33°, 0.2674 M. sodium ethoxide/ethanol[a].

Time elapsed	Absorbance	$\log \frac{A_\infty - A_o}{A_\infty - A_t}$
0	0.170	---
8,003	0.198	0.01043
23,779	0.224	0.02073
45,902	0.248	0.02920
Graphical rate[b]		1.08×10^{-6}
82,717	0.265	0.03645
178,949	0.274	0.04021
395,088	0.292	0.04739
566,700	0.296	0.04904
Graphical rate[c]		7.41×10^{-8}

[a]Conc. of bromide = 9.176×10^{-3} M., substrate was allowed to react for 20 minutes prior to zero point, calculated infinity point is 1.350.

[b]Straight line drawn through the first 3 points (A_∞ = 1.35), computer rate = $1.16 \pm 0.07 \times 10^{-6}$, graphical rate $k_1 = 3.31 \times 10^{-5}$ if the extrapolated infinity point of 0.269 is used, computer rate (A_∞ = 0.269) = $3.23 \pm 0.08 \times 10^{-5}$.

[c]Straight line drawn through the last 4 points (A_∞ = 1.35), computer rate = $6.17 \pm 0.52 \times 10^{-8}$.

Table 57. Solvolysis of cis- and trans-2-phenylcyclopentyl bromide, 70.33°, sodium acetate/ethanol[a].

Time elapsed	Absorbance	$\log \frac{A_\infty - A_0}{A_\infty - A_t}$	$k_1 \times 10^5$
Blank[b]	0.009	---	----
0	0.051	---	----
7,676	0.077	0.13077	3.92
21,842	0.109	0.37675	3.97
39,293	0.130	0.67778	3.97
77,816	0.145	1.22185	3.62
100,250	0.149	1.69897	3.90
Average rate[c]			3.88 ± 0.10
124,094	0.151	0.03788	
180,074	0.160	0.04146	
536,405	0.183	0.05074	
Graphical rate[d]			7.07×10^{-8}

[a]Concentration of sodium acetate = 0.268 M., concentration of bromide = 8.474×10^{-3} M.

[b]Blank was measured on the bromide mixture in anhydrous ethanol and diluted the same as kinetic points, substrate was allowed to react for 20 minutes prior to zero point.

[c]Graphical rate = 3.81×10^{-5}, computer rate = 3.78 ± 0.08, infinity point was extrapolated as 0.151, graphical rate using $A_\infty = 1.248$ through these points gave $k_1 = 1.04 \times 10^{-6}$.

[d]Straight line drawn through the last 5 points using the calculated infinity point 1.248, computer rate = $7.30 \pm 0.45 \times 10^{-8}$.

Vapor phase pyrolysis

Procedure for pyrolysis Pyrolyses were carried out by slowly dropping the liquid esters through an externally-heated column. Nitrogen was slowly passed through the column at a rate of 14-16 mls. per minute and the products were collected in an ice-acetone trap at the bottom of the column. The pyrolysis column was a vertically mounted glass tube 24 in. in length and 3/4 in. in diameter. It was packed (11 in. of its length) with pyrex glass wool and the internal temperature of the column was determined using an iron vs. constantan thermocouple.

After pyrolysis, the column was washed with ether and the acetic acid was removed by one extraction with a saturated sodium bicarbonate solution. Most of the ether was carefully distilled and the remaining solution was analyzed directly by gas phase chromatography. In the runs which were analyzed by NMR to determine the olefin ratios, carbon tetrachloride was used to wash the column. After extraction with bicarbonate, most of the solvent was distilled using a 6 inch glass helices packed column. The NMR was taken directly on the filtered residue. The products from the pyrolysis of cyclopentyl acetate were collected in a dry ice-acetone trap and immediately injected into the GPC to avoid loss of the volatile olefin. A second trap connected in series with the first contained a very small amount of olefin.

Analysis of products The olefinic products formed from the pyrolysis of 2- and 3-t-butylcyclopentyl acetates and 3-phenylcyclopentyl acetates were analyzed by GPC using an Aerograph Hi-Fi (M 600-C) Gas Chromatograph with a flame ionization detector. t-Butyl olefins were separated at 100° using a 25 ft. (1/8 in.) copper column packed with 5%

bis (ethyl hexyl) tetrachlorophthalate on 80-100 mesh Chromosorb W (HMDS treated) and the phenyl olefins were separated at 110° using a 25 ft. (1/8 in.) copper column packed with 10% Zonel E-7 on 60-80 mesh Chromosorb W (HMDS treated). The ratio of 1- to 3-t-butylcyclopentene was also measured by NMR. The F & M Gas Chromatograph equipped with a 4 ft. LAC 446 column was used for determining the ratio of 1-phenylcyclopentene to 3-phenylcyclopentene and the per cent conversions of the acetates to their respective olefins.

The pyrolysis of an equimolar mixture of 3-t-butylcyclopentene and anhydrous acetic acid demonstrated no isomerization of olefins was occurring under the pyrolysis conditions. This was also shown by Smat (89) to be the case for the phenylcyclopentenes.

Relative rates of pyrolysis The relative rates of pyrolysis of a mixture of trans-2-t-butylcyclopentyl acetate and trans-2-phenylcyclopentyl acetate were measured at three temperatures using chlorobenzene as an internal standard. A blank solution and the pyrolysate were identically taken up in ether and extracted with bicarbonate solution. After most of the ether was carefully distilled, the sample was analyzed with the F and M GPC using a 4 ft. LAC 446 column. The temperature was programmed from 100° to 200°. The equation derived by Weissberger (144) was used to calculate the relative rates.

$$\frac{k_{\text{trans-2-t-butyl}}}{k_{\text{trans-2-phenyl}}} = \frac{\log \frac{[\text{trans-2-t-butyl}]i}{[\text{trans-2-t-butyl}]f}}{\log \frac{[\text{trans-2-phenyl}]i}{[\text{trans-2-phenyl}]f}}$$

The relative pyrolytic rates of cis-2-t-butylcyclopentyl acetate and cis-2-phenylcyclopentyl acetate were determined in a similar manner,

except an internal standard was not used to determine the initial and final concentrations of the acetates (a small loss of the internal standard due to its greater volatility has an effect on the relative rate ratio, since the acetate reactivities vary greatly in this instance). The equation in this case used the initial and final ratios of the acetates and the per cent conversion of cis-3-phenylcyclopentyl acetate to olefin in order to calculate the relative rates of pyrolysis at a given temperature.

$$\frac{k_A}{k_B} = \frac{\log \frac{\left(\frac{A}{B}\right)_i}{\left(\frac{A}{B}\right)_f^{xBf}}}{\log \frac{1}{1-x}}$$

where B_i (the initial concentration of cis-2-phenylcyclopentyl acetate) is set equal to 1.

$\left(\frac{A}{B}\right)_i$ is the initial ratio of cis-2-t-butylcyclopentyl acetate to cis-2-phenylcyclopentyl acetate.

$\left(\frac{A}{B}\right)_f$ is the final ratio after pyrolysis.

$Bf = 1-x$.

x = per cent phenyl olefin formed.

The ratio of 3-phenylcyclopentene to cis-2-phenylcyclopentyl acetate was corrected for thermal conductivity differences in the GPC analysis.

SUMMARY

The synthesis of the isomeric cis- and trans-2- and 3-t-butylcyclopentanols was reported. The nuclear magnetic resonance spectra of the variously substituted t-butyl, phenyl and isopropyl compounds as a function of steric and conformational effects was discussed, along with their effects on the chemical reactivity and product ratios from equilibration of the alcohols, epoxidation of the 3-olefins, reduction of the cis- and trans-epoxides with lithium aluminum hydride and Raney nickel, hydroboration of the 3-olefins, and bromination of the alcohols.

Kinetics and product ratios from the potassium t-butoxide---promoted elimination of a number of cyclopentyl derivatives were studied. Solvolysis was shown to be absent in the unsubstituted cyclopentyl compounds by a quantitative determination of the olefin produced and a study of the reaction rate versus base concentration. Competing solvolysis and elimination rates were separated from the product olefin ratios in the cis- and trans-2-t-butylcyclopentyl p-toluenesulfonates assuming pseudo first order reaction conditions. The relative elimination rates from a number of 2- and 3-t-butyl- and phenylcyclopentyl bromides and p-toluenesulfonates were determined and explained on the basis of steric effects, conformational influences on the dihedral angle, and solvation of the leaving group. Elimination of cis-2-phenylcyclopentyl bromide was shown to occur faster than the corresponding p-toluenesulfonate by a factor of 41, whereas the cis-elimination occurring in trans-2-phenylcyclopentyl bromide is 12 times slower than that in the tosyloxy compound. A correlation is proposed for the bromide-p-toluenesulfonate rate ratio as a function of the position of

a given compound in the mechanistic E2 transition state spectrum.

The per cent reaction, product olefin ratio, and relative rates of elimination were studied at various temperatures (350-500°) for the vapor phase pyrolyses of cyclopentyl acetate and a number of 1,2, and 3-substituted phenyl- and t-butylcyclopentyl acetates. The relative rates of pyrolysis and the product ratios were discussed in terms steric, thermodynamic, statistical, and conformational effects.

LITERATURE CITED

1. A. von Baeyer, Ber., 18, 2277 (1885).

2. W. v. E. Doering and M. Farber, J. Am. Chem. Soc., 71, 1514 (1949).

3. E. Eliel, N. Alliger, S. Angyal and G. Morrison, "Conformational Analysis," Interscience Publishers, New York, N.Y., (1965).

4. M. Hanack, "Conformation Theory," Academic Press, New York, N.Y., (1965).

5. J. Kilpatrick, K. Pitzer and R. Spitzer, J. Am. Chem. Soc., 69, 2483 (1947).

6. K. Pitzer and W. Donath, J. Am. Chem. Soc., 81, 3213 (1959).

7. J. Ashton, S. Schuman, H. Fink and P. Doty, J. Am. Chem. Soc., 63, 2029 (1941).

8. A. Almenningen, O. Bastiansen and P. Skancke, Acta Chem. Scand., 15, 711 (1961).

9. F. Brutcher, Jr., T. Roberts, S. Barr and N. Pearson, J. Am. Chem. Soc., 81, 4915 (1959).

10. E. Eliel, "Steriochemistry of Carbon Compounds," McGraw-Hill Book Company, Inc., New York, N.Y., (1962).

11. J. Reisse, L. Nagels and G. Chiurdoglu, Bull. Soc. Chim. Belges, 74, 162 (1965).

12. J. McCullough, R. Pennington, J. Smith, I. Hossenlopp and G. Waddington, J. Am. Chem. Soc., 81, 5880 (1959).

13. O. Wheeler and E. de Rodrigue, J. Org. Chem., 29, 718 (1964).

14. C. Beckett, N. Freeman and R. Pitzer, J. Am. Chem. Soc., 70, 4227 (1948).

15. G. Rathjens, J. Chem. Phys., 21, 1229 (1953).

16. R. Turner and W. Meador, J. Am. Chem. Soc., 79, 4133 (1957).

17. M. Epstein, G. Barrow, K. Pitzer and F. Rossini, J. Res. Natl. Bur. Stand., 43, 245 (1949).

18. W. Hückel and J. Kurz, Ann., 645, 194 (1961).

19. K. Kozima and W. Suetaka, J. Chem. Phys., 35, 1516 (1961).

20. L. Kuhn, J. Am. Chem. Soc., 74, 2492 (1952).

21. L. Schotsmans, P. Fierens and T. Verlie, Bull. Soc. Chim. Belges, 68, 580 (1959).

22. C. Overberger, H. Biletch, A. Finestone, J. Lilker and J. Herbert, J. Am. Chem. Soc., 75, 2078 (1953).

23. W. Kumler and A. Huitric, J. Am. Chem. Soc., 78, 3369 (1956).

24. H. Goering and K. Howe, J. Am. Chem. Soc., 79, 6542 (1957).

25. W. Hückel and E. Mogle, Ann., 649, 13 (1961).

26. W. Hückel and R. Bross, Ann., 664, 1 (1963).

27. W. Hückel, R. Bross, O. Fechtig, H. Feltkamp, S. Geiger, M. Hanack, M. Heinzel, A. Hubele, J. Kurz, M. Maier, D. Maucher, R. Neidlein and R. Rashingkar, Ann., 624, 142 (1959).

28. W. Hückel and R. Bross, Ann., 685, 118 (1965).

29. H. Brown and F. Chloupek, J. Am. Chem. Soc., 85, 2522 (1963).

30. I. Lillien and K. Khaleeluddin, Chem. and Ind., 1023 (1965).

31. J. Weinstock, K. Pearson and F. Bordwell, J. Am. Chem. Soc., 78, 3468, (1956).

32. J. Smith, "Bimolecular Elimination Reactions of Cyclopentyl Compounds." Unpublished Ph.D. thesis. Library, Iowa State University of Science and Technology, Ames, Iowa. (1964).

33. C. DePuy, G. Morris, J. Smith and R. Smat, J. Am. Chem. Soc., 87, 2421 (1965).

34. C. DePuy, R. Thurn and G. Morris, J. Am. Chem. Soc., 84, 1314 (1962).

35. C. Ingold, "Structure and Mechanism in Organic Chemistry," Cornell University Press, Ithaca, N.Y., (1953).

36. E. Hughes, J. Am. Chem. Soc., 57, 708 (1935).

37. E. Gould, "Mechanism and Structure in Organic Chemistry," Holt, Rinehart and Winston, New York, N.Y. (1959).

38. D. Banthorpe, "Elimination Reactions," Elsevier Publ. Co., New York, N.Y. (1963).

39. J. Hine, "Physical Organic Chemistry," McGraw-Hill Book Co., Inc., New York, N.Y. (1962).

40. J. Hine, R. Wiesboeck and O. Ramsay, J. Am. Chem. Soc., 83, 1222, (1961).

41. S. Cristol and D. Fix, J. Am. Chem. Soc., 75, 2647 (1953).

42. S. Cristol and N. Hause, J. Am. Chem. Soc., 74, 2193 (1952).

43. S. Cristol and E. Hoegger, J. Am. Chem. Soc., 79, 3438 (1957).

44. S. Cristol and R. Arganbright, J. Am. Chem. Soc., 79, 3441 (1957).

45. J. Hine and O. Ramsay, J. Am. Chem. Soc., 84, 973 (1962).

46. F. Bordwell, R. Arnold and J. Biranowski, J. Org. Chem., 28, 2496, (1963).

47. H. Goering, D. Relyea and K. Howe, J. Am. Chem. Soc., 79, 2502 (1957).

48. R. Breslow, Tetrahedron Letters, 8, 399 (1964).

49. W. Hanhart and C. Ingold, J. Chem. Soc., 997 (1927).

50. J. Bunnett, Angew. Chem. Intern. Ed., 1, 225 (1962).

51. W. Saunders and S. Asperger, J. Am. Chem. Soc., 79, 1612 (1959).

52. E. Buncel and A. Bourns, Can. J. Chem., 38, 2457 (1960).

53. G. Ayrey, A. Bourns and V. Vyas, Can. J. Chem., 41, 1759 (1963).

54. K. Wiberg, Chem. Rev., 55, 713 (1955).

55. F. Westheimer, Chem. Rev., 61, 265 (1961).

56. K. Wiberg and E. Motell, Tetrahedron Letters, 19, 2009 (1963).

57. L. Steffa, and E. Thornton, J. Am. Chem. Soc., 85, 2680 (1963).

58. M. Newman, "Steric Effects in Organic Chemistry," J. Wiley and Sons, New York, N.Y. (1956).

59. D. Barton and W. Rosenfelder, J. Chem. Soc., 1048 (1951).

60. S. Cristol, F. Stermitz and P. Ramey, J. Am. Chem. Soc., 78, 4939 (1956).

61. S. Cristol and F. Stermitz, J. Am. Chem. Soc., 82, 4693 (1960).

62. P. Skell and J. MacNamara, J. Am. Chem. Soc., 79, 85 (1957).

63. W. Smith and W. Watson, J. Am. Chem. Soc., 84, 3174 (1962).

64. N. LeBel, P. Beirne and P. Subramanian, J. Am. Chem. Soc., 86, 4144 (1964).

65. N. LeBel, P. Beirne, E. Karger, J. Powers and P. Subramanian, J. Am. Chem. Soc., 85, 3199 (1963).

66. S. Cristol and P. Pappas, J. Org. Chem., 28, 2066 (1963).

67. J. Zauada and J. Sicher, Proc. Chem. Soc., 96 (1963).

68. S. Cristol, N. Hause and J. Meek, J. Am. Chem. Soc., 73, 674 (1951).

69. N. LeBel, P. Beirne, E. Karger, J. Powers and P. Subramanian, J. Am. Chem. Soc., 85, 3199 (1963).

70. N. LeBel, P. Beirne and P. Subramanian, J. Am. Chem. Soc., 86, 4144 (1964).

71. S. Patai, "The Chemistry of the Alkenes," Interscience Publishers, New York, N.Y., (1964).

72. D. Cram, F. Greene and C. DePuy, J. Am. Chem. Soc., 78, 790 (1956).

73. J. Zavada and J. Sicher, Coll. Czech. Chem. Comm., 30, 438 (1965).

74. A. Colter and R. Johnson, J. Am. Chem. Soc., 84, 3289 (1962).

75. A. Colter and D. McKelvey, Can. J. Chem., 43, 1282 (1965).

76. J. Csapilla, Chimia, 18, 37 (1964).

77. W. Saunders, S. Fahrenholtz and J. Lowe, Tetrahedron Letters, 18, 1 (1960).

78. W. Saunders, S. Fahrenholtz, E. Caress, J. Lowe and M. Schreiber, J. Am. Chem. Soc., 87, 3401 (1965).

79. D. Froemsdorf and M. McCain, J. Am. Chem. Soc., 87, 3983 (1965).

80. D. Froemsdorf, M. McCain and W. Wilkison, 87, 3984 (1965).

81. C. Bishop, "Pyrolytic and Base Catalyzed Elimination Reactions: Effect of Structure on the Rate of Reaction," Unpublished Ph.D. thesis, Library, Iowa State University of Science and Technology, Ames, Iowa (1961).

82. J. Frey, "Solvent and Structural Effects on Bimolecular Elimination Reactions," Unpublished Ph.D. thesis, Library, Iowa State University of Science and Technology, Ames, Iowa (1964).

83. C. DePuy and R. King, Chem. Rev., 60, 431 (1960).

84. D. Froemsdorf, "Directive Effects in Elimination Reactions," Unpublished Ph.D. thesis, Library, Iowa State University of Science and Technology, Ames, Iowa (1959).

85. R. Taylor, G. Smith and W. Wetzel, J. Am. Chem. Soc., 84, 4817 (1962),

86. G. Smith, D. Jones and D. Brown, J. Org. Chem., 28, 403 (1963).

87. A. Maccoll, "Theoretical Organic Chemistry: Kekule Symposium," Butterworth and Co., Ltd., London, England, (1959).

88. A. Maccoll, "Advances in Physical Organic Chemistry," Volume 3, Academic Press, New York, N.Y. (1965).

89. R. Smat, "Synthesis and Elimination Reactions of Cyclopentanol and Its Derivatives," Unpublished M.S. thesis, Library, Iowa State University of Science and Technology, Ames, Iowa (1962).

90. H. Brown, J. Brewster and H. Shechter, J. Am. Chem. Soc., 76, 467 (1954).

91. C. DePuy and R. King, J. Am. Chem. Soc., 83, 2743 (1961).

92. E. Eliel and C. LuKach, J. Am. Chem. Soc., 79, 5986 (1957).

93. S. Winstein and N. Holness, J. Am. Chem. Soc., 77, 5562 (1955).

94. G. Crane, C. Boord and A. Henne, J. Am. Chem. Soc., 67, 1237 (1945).

95. R. Thurn, "Base Promoted cis-Eliminations," Unpublished Ph.D. thesis, Library, Iowa State University of Science and Technology, Ames, Iowa (1964).

96. H. Brown, "Hydroboration," W. A. Benjamin, Inc., New York, N.Y., (1962).

97. H. Brown and G. Zweifel, J. Am. Chem. Soc., 83, 2544 (1961).

98. H. Brown, N. Ayyangar and G. Zweifel, J. Am. Chem. Soc., 86, 397 (1964).

99. G. Zweifel, N. Ayyangar, T. Munekata and H. Brown, J. Am. Chem. Soc., 86, 1075 (1964).

100. W. Dauben, G. Fonken and D. Noyce, J. Am. Chem. Soc., 78, 2579 (1956).

101. B. Yager and C. Hancock, J. Org. Chem., 30, 1174 (1965).

102. V. Shiner and D. Whittaker, J. Am. Chem. Soc., 85, 2337 (1963).

103. W. Moulton, R. VanAtta and R. Ruch, J. Org. Chem., 26, 290 (1961).

104. V. Shiner, D. Whittaker and V. Fernandez, J. Am. Chem. Soc., 85, 2318 (1963).

105. S. Temin and M. Baum, Can. J. Chem., 43, 705 (1965).

106. W. Dauben, G. Fonken and D. Noyce, J. Am. Chem. Soc., 78, 2579 (1956).

107. R. Buckles and J. Maurer, J. Org. Chem., 18, 1585 (1953).

108. C. Guss and R. Rosenthal, J. Am. Chem. Soc., 77, 2549 (1955).

109. B. Rickborn and L. Shiow-Yueh, J. Org. Chem., 30, 2212 (1965).

110. H. Henbest, Proc. Chem. Soc., 159 (1963).

111. R. Parker and N. Isaacs, Chem. Rev., 59, 737 (1959).

112. M. Newman, G. Underwood and M. Renold, J. Am. Chem. Soc., 71, 3362 (1949).

113. G. Park and R. Fuchs, J. Org. Chem., 22, 93 (1957).

114. O. Chapman and R. King, J. Am. Chem. Soc., 86, 1257 (1964).

115. C. Johnson Jr., F. Bovey, J. Chem. Phys. 29, 1012 (1958).

116. G. Wiley, R. Hershkowitz, B. Rein and B. Chung, J. Am. Chem. Soc., 86, 964 (1964).

117. J. Schaefer and D. Weinberg, J. Org. Chem., 30, 2635 (1965).

118. P. Levene and A. Rothen, J. Biol. Chem., 127, 237 (1939).

119. C. Bishop and C. DePuy, Chem. and Ind., 297 (1959).

120. C. Bumgardner, Chem. Comm., 374 (1965).

121. P. Veeravagu, R. Arnold and E. Eigenmann, J. Am. Chem. Soc., 86, 3072 (1965).

122. H. Brown and R. Klimisch, J. Am. Chem. Soc., 87, 5517 (1965).

123. C. Swain and E. Thornton, Tetrahedron Letters, 211 (1961).

124. C. Swain and E. Thornton, J. Am. Chem. Soc., 84, 817 (1962).

125. S. Siggia, "Quantitative Organic Analysis Via Functional Groups," New York, N.Y., John Wiley and Sons, Inc., (1954).

126. J. Germain, L. Basserby and R. Maurel, Compt. Rend., 260, 560 (1965).

127. W. Young and L. Andrews, J. Am. Chem. Soc., 66, 421 (1944).

128. S. Siggia and J. Hanna, Anal. Chem., 33, 896 (1961).

129. W. Bailey and W. Hale, J. Am. Chem. Soc., 81, 651 (1959).

130. D. Froemsdorf, C. Collins, G. Hammond, and C. DePuy, J. Am. Chem. Soc., 81, 643 (1959).

131. C. Kingsbury and D. Cram, J. Am. Chem. Soc., 82, 1810 (1960).

132. H. C. Brown, N. R. Ayyangar and G. Zweifel, J. Am. Chem. Soc., 86, 1071 (1964).

133. G. Zweifel and H. C. Brown, J. Am. Chem. Soc., 86, 393 (1964).

134. N. L. Allinger and S. Greenberg, J. Am. Chem. Soc., 84, 2394 (1962).

135. K. Bowden, I. M. Heilbron, E. R. H. Jones, and B. C. L. Weedon, J. Chem. Soc., 39 (1946).

136. W. H. Tallent, J. Org. Chem., 21, 862 (1956).

137. M. T. Rogers and J. D. Roberts, J. Am. Chem. Soc., 68, 843 (1946).

138. R. S. Tipson, J. Org. Chem., 9, 235 (1944).

139. S. H. Langer, S. Connell, and I. Wender, J. Org. Chem., 23, 50 (1958).

140. A. I. Vogel, "Practical Organic Chemistry," London, England, Longmans, Green and Co. (1956).

141. E. E. Royals and L. L. Harrell, J. Am. Chem. Soc., 77, 3405 (1955).

142. R. Mozingo, Organic Syntheses, Collective Volume III, 181 (1955).

143. R. Adams and R. L. Shriner, J. Am. Chem. Soc., 45, 2171 (1923).

144. S. L. Friess, E. S. Lewis, and A. Weissberger, "Technique of Organic Chemistry," Vol. VIII. New York, N.Y., Interscience Publishers Inc., (1961).

145. C. H. DePuy and P. R. Story, J. Am. Chem. Soc., 82, 627 (1960).

146. R. H. Manske, J. Am. Chem. Soc., 53, 1106 (1931).

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr. C. H. DePuy for his interest, encouragement and assistance throughout the course of this work, especially since communication between Ames, Iowa and Boulder, Colorado was difficult.

He is also indebted to Dr. G. F. Morris for the numerous discussions and suggestions which were helpful in the preparation of this work.

He wishes to thank his wife, Polly, for her encouragement, understanding and patience during the past three years and likewise her assistance in the preparation and typing of this dissertation; he also wishes to thank his parents, for their encouragement and guidance throughout his education.

The author acknowledges the financial assistance of the Shell Companies Foundation.